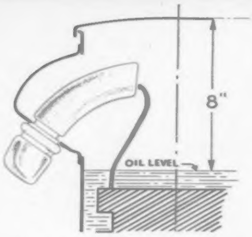
ALLIS-CHALMERS

Electrical REVIEW

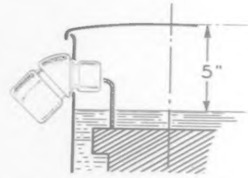
Second Quarter, 1949

NOW..

- **Tank Height Reduced!**
- **Bushing Pockets Eliminated!**
- **Bushing Clamp Simplified!**



OLD DESIGN required more space above oil level because of longer bushing shank.



NEW BUSHING saves up to 3" in tank height . . . eliminates need for bushing pockets.

EXPLODED VIEW shows the simplicity of the new bushing clamping arrangement.

A-2704

. . . on Allis-Chalmers Distribution Transformers

ALLIS-CHALMERS NEW TANK-WALL BUSHING eliminates all need for high voltage bushing pockets . . . enables up to 3" reductions in tank height. This means even greater compactness . . . easier handling distribution transformers than ever before! (Reductions are *in addition* to savings in size and weight through use of highly oriented core steel.)

Installation of the bushing itself is simplified because there are fewer parts, and no critical porcelain tolerances between bushing and keeper. A cushion-like spring on the inner side of the tank wall, between the keeper and bushing absorbs any shock or strain during handling. Increased wall thickness of the bushing, together with straighter, shorter shank contour, increases mechanical strength.

AVAILABLE ON UNITS UP TO 150 KVA

The new design is available on transformers from 3 to 100 kva, single phase, and from 9 to 150 kva, three phase, in voltages up to 4800/8320Y.

For further details on this new bushing, or for other facts on Allis-Chalmers quality distribution transformers, call your nearby A-C sales representative.

ALLIS-CHALMERS, 848A SO. 70 ST.
MILWAUKEE, WISCONSIN

ALLIS-CHALMERS

Pioneers in Power and Electrical Equipment from Generation through Utilization

A-C
ALLIS-CHALMERS

WAVERING LINE VOLTAGE on rural power lines will soon be as out-of-date as the kerosene lanterns that preceded the lights. A new low-priced, pole-mounted feeder regulator has just been made available. On the cover, G. W. Clothier, manager of the transformer section, is shown pointing out features of the new step-type regulator to R. M. Casper, newly-appointed manager of the electrical department of the Allis-Chalmers Mfg. Co.

The 7.2-kv, 10.8-kva unit is shown after undergoing the full schedule of impulse testing. More complete details of this promising new regulator, shown above during field test, appear on page 14.

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Allis-Chalmers

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DR. ERWIN SALZER

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the VOLTOR diagram

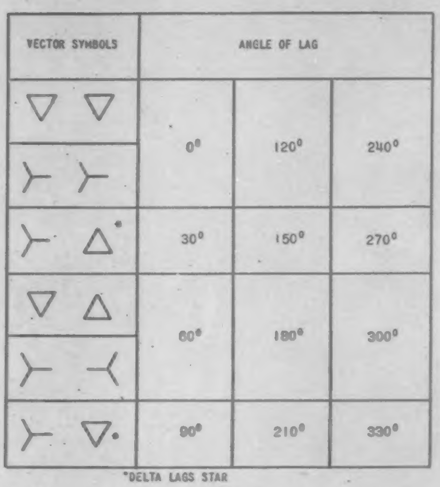


TABLE 1 — The 12 angles of lag associated with vector symbols may be obtained from the Voltor Diagram.

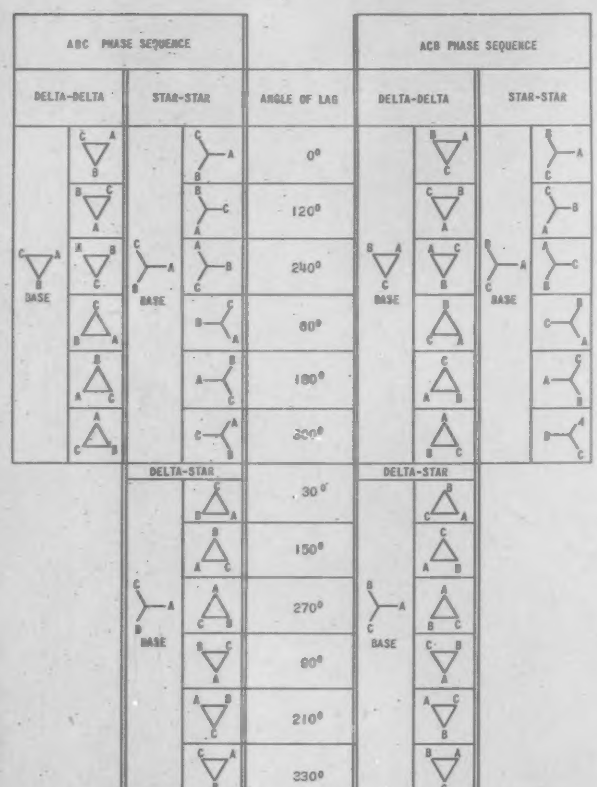


TABLE 2 — Phase rotation and relative phasing associated with vector symbols of TABLE 1.

NOTE: Counter-clockwise rotation ACB phase sequence is identical with ABC except that B and C phases have been interchanged.

E. S. WARNER
Supervising Engineer, Engineering Dept.
Commonwealth Edison Company

Simplified method of using voltage vectors aids determination of 3-phase transformer connections.

THE VOLTAGE CHARACTERISTICS of three-phase transformer banks are such that phase shifts are introduced by the connections at the terminals and windings. Operating engineers usually are not interested in the angular displacement of the various voltages; but there are times when it is of utmost importance to know the phase shift through a transformer bank.

If electrical phase shifts occur through transformer banks in series and if the system is to form a closed loop, then it is important to connect the ends of the system together to form the loop so that the respective voltages are in phase. Transformer banks in parallel must also be connected in phase. A knowledge of the phase shift through each transformer bank, the total shift of the final transformer bank relative to the first one and a means of shifting phases so that when the loop is closed the first and last transformer banks are in phase, are all important.

It is a relatively simple matter to determine the phase shift between any two windings by making vector diagrams of the two windings involved. The difficulty is usually encountered when the information from the vector diagrams is used to determine the physical connections at the transformer terminals; and it is the purpose of the Voltor Diagram to simplify this procedure.

Vector symbols

When vector symbols are used without phase identification the 12 angles of lag are shown in Table 1. These symbolic combinations may be obtained from the Voltor Diagram, one symbol for each winding.

When vector symbols are used with phase identification, the associated angles of lag are shown in Table 2.

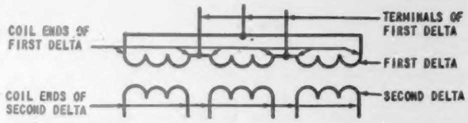
If the angle of lag is to be fixed, the phases must be identified; otherwise there are three possible angles of lag for each pair of vector symbols.

The voltor diagram method

The Voltor Diagram method is based on the establishment of the A-phase connection of the basic winding, the measurement of the angle of lag between the A-phase basic and the

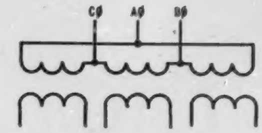
TABLE 3 — Procedure for DELTA-DELTA connections.

1 — BASIC DIAGRAM AND TERMINOLOGY

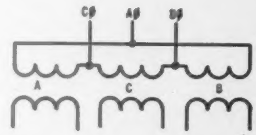


PROCEDURE
(ABC Phase Sequence)
(See Note 7)

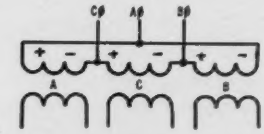
2 — Mark The Terminals Of The First Delta (A, B, C Φ) In Any Order.



3 — Mark The Coils Of The First Delta (A, B, C) So That The AΦ Terminal Is Between The "A" and "B" Coils. (See Note 1)



4 — Mark (+) The End of "A" Coil Nearest AΦ Terminal Of The First Delta. Do The Same For "B" and "C" Coils. Mark The Opposite Ends Of These Coils (—).



A-phase lagging windings, and the determination of the A-phase connection of the lagging winding. B- and C-phases follow in order on the diagrams.

There are three variable quantities in three phase transformations:

1—the connections of the basic windings,

2—the angular displacement or angle of lag, and

3—the connections of the lagging windings.

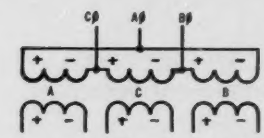
When any two of these three quantities have been established, the third may be obtained by mere inspection if the Voltor Diagram method is used, otherwise the process may be quite involved. Once the method is understood, the only part of this article necessary for the solution of problems is either Figure 1 for *ABC* phase sequence or Figure 2 for *ACB* phase sequence.

The vector symbols used from the Voltor Diagram is that shown for only the A-phase of the Basic windings and that for only A-phase of the lagging windings. The combination of these two vector symbols constitute the only one used for a specific angle of lag as shown in Table 2 and not one of the general vectors as shown in Table 1.

The procedure to be followed in determining the connections and voltage vector relations is outlined in Tables 1, 2 and 3 for the following winding connections, Delta-Delta, Delta-Star, and Star-Star.

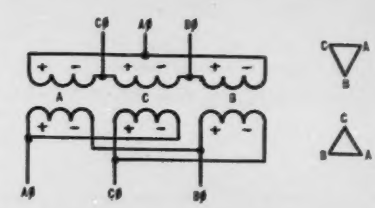
By following the procedure outlined in the proper table step by step, the physical connections for a given phase shift may be determined. In each case the procedure is illustrated

5 — Mark The Coil Ends Of The Second Delta To Agree With The First Delta.



6 — From The Use Of The ABC Voltor Diagram (Fig. 1, See Problem 1) AΦ Of The Second Delta Is The Junction Of The (+) End of "A" Coil And The (—) End Of "C" Coil.

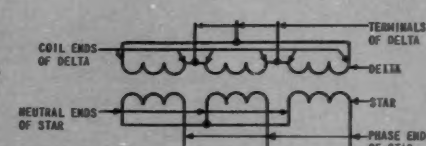
Also BO = +B—A
CO = +C—A



Therefore In The Second Delta, Join Each (+) End of "A" Coil With One (—) End And Mark The Junctions (A, B, C Φ) In Accordance With The Above And Add The Vector Symbols.

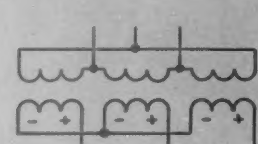
TABLE 4 — Procedure for DELTA-STAR connections.

1 — BASIC DIAGRAM AND TERMINOLOGY

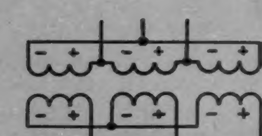


PROCEDURE
(ABC Phase Sequence)
(See Note 4)

2 — Mark The Phase Ends Of The Star (+) And The Neutral Ends (—).



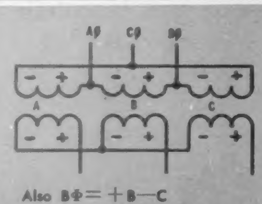
3 — Mark The Coil Ends Of The Delta In A Similar Manner. (See Note 2)



4 — Mark The Terminals And Coils Of The Delta In Any Order To Agree With The Following:

From The Use Of The ABC Voltor Diagram (Problem 2):

AΦ Delta Is The Junction Of The (+) End Of The "A" Coil And The (—) End Of The "B" Coil.



Also BΦ = +B—C
CΦ = +C—A

5 — Mark The Phase Ends Of The Star (A, B, C Φ) To Agree With The Phasing Of The Coils, And Add The Vector Symbols.

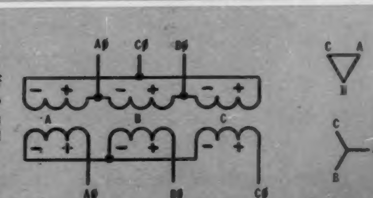
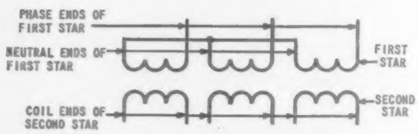


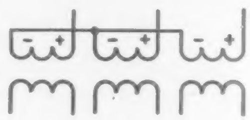
TABLE 5 — Procedure for STAR-STAR connections.

1 — BASIC DIAGRAM AND TERMINOLOGY

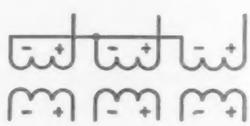


PROCEDURE
(ABC Phase Sequence)
(See Note 6)

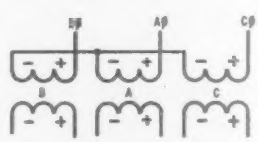
2 — Mark The Phase Ends Of The First Star (+) And The Neutral Ends (—).



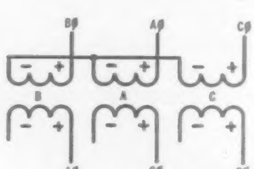
3 — Mark The Coil Ends Of The Second Star Similar To The First Star. (See Note 5)



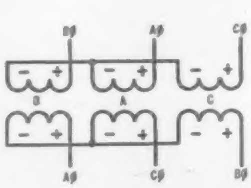
4 — Mark The Phase Ends Of The First Star (A, B, C Φ) In Any Order, And The Coils Of Both Stars (A, B, C) In Agreement With The Phase Ends Of The First Star.



5 — From The Use Of The ABC Voltor Diagram (Problem 3) The A Phase End Of The Second Star Is The (+) End Of The B Coil, Also BΦ = +C
CΦ = +A
Therefore Mark As Phase Leads of The Second Star The Above Arrangement.



6 — Join The Remaining Ends Of The Second Star To Form A Neutral, And Add The Vector Symbols.



by a later example in order to show how it is applied at each step.

Typical problems illustrate application

ABC Phase Sequence

1—*Delta-Delta* (use Figure 1)

Requirements: The first Delta lags the second Delta by 60 degrees.

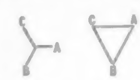
Procedure: From position +A-B measure an angle of 60 degrees (2 units of 30 degrees) in a direction clockwise (opposite to *ABC* arrow) to position +A-C. This means that the A-phase terminal of the 2nd Delta is the junction of the (+) end of "A" coil and the (—) end of "C" coil, and the associated vector symbol is:

The B- and C-phase terminals follow in order clockwise in Figure 1, B-phase 120 degrees from A-phase, and C-phase 120 degrees from B-phase. The vector symbols for B- and C-phases are not used.

2—*Delta-Star* (use Figure 1)

Requirements: The Delta lags the Star by 330 degrees.

Procedure: From position +A measure an angle of 330 degrees (11 units of 30 degrees) in a direction clockwise (opposite to *ABC* arrow) to position +A-B. This means that the A-phase terminal of the Delta is the junction of the (+) end of the "A" coil and the (—) end of the "B" coil, and the associated vector symbol is:

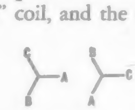


The B- and C-phase terminals follow in order clockwise in Figure 1, B-phase 120 degrees from A-phase and C-phase 120 degrees from B-phase. The vector symbols for B- and C-phases are not used.

3—*Star-Star* (use Figure 1)

Requirements: The 2nd Star lags the 1st Star by 120 degrees.

Procedure: From position +A measure an angle of 120 degrees (4 units of 30 degrees) in a direction clockwise (opposite to *ABC* arrow) to position +B. This means that the A-phase terminal of the 2nd Star is the (+) end of "B" coil, and the associated vector symbol is:



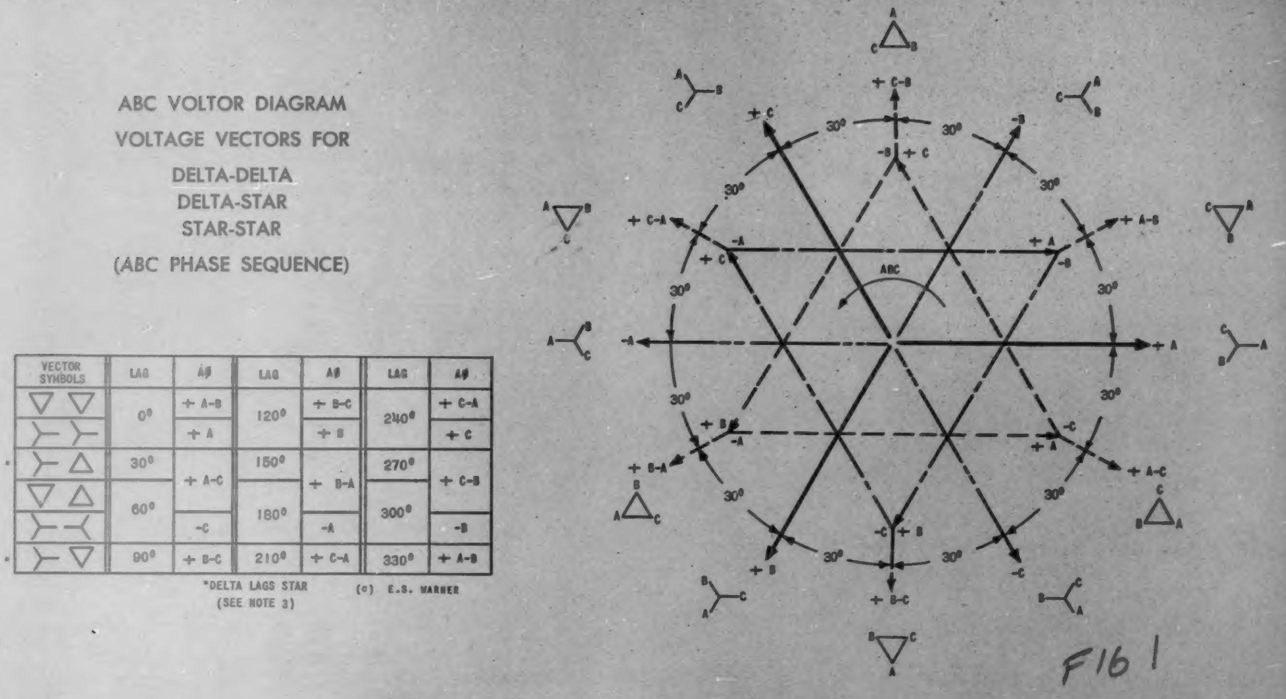
B- and C-phase terminals follow in order clockwise in Figure 1, B-phase 120 degrees from A-phase and C-phase 120 degrees from B-phase. The vector symbols for B- and C-phases are not used.

ACB Phase Sequence

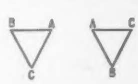
4—*Delta-Delta* (use Figure 2)

Requirements: The 1st Delta lags the 2nd Delta by 240 degrees.

Procedure: From position +A-C measure an angle of 240 degrees (8 units of 30 degrees) in a direction clock-



wise (opposite to *ACB* arrow) to position +B-A. This means that the A-phase terminal of the 2nd Delta is the junction of the (+) end of "B" coil and the (—) end of "A" coil, and the associated vector symbol is:

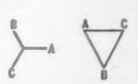


The C- and B-phase terminals follow in order clockwise in Figure 4, C-phase 120 degrees from A-phase, and B-phase 120 degrees from C-phase. The vector symbols for C- and B-phases are not used.

5—*Delta-Star* (use Figure 2)

Requirements: The Delta lags the Star by 210 degrees.

Procedure: From position +A measure an angle of 210 degrees (7 units of 30 degrees) in a direction clockwise (opposite to *ACB* arrow) to position +B-A. This means that the A-phase terminal of the Delta is the junction of the (+) end of "B" coil and the (—) end of "A" coil, and the associated vector symbol is:

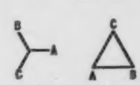


The C- and B-phase terminals follow in order clockwise in Figure 2. C-phase is 120 degrees from A-phase, and B-phase 120 degrees from C-phase. The vector symbols for C- and B-phases are not used.

6—*Delta-Star* (use Figure 2)

Requirements: The Star lags the Delta by 210 degrees.

Procedure: Since the Voltor Diagram is to be used with the Delta lagging the Star, 360 degrees minus 210 equals 150 degrees. The Delta lags the Star this much, which is the same as the Star lagging the Delta by 210 degrees. Therefore from position +A measure an angle of 150 degrees (5 units of 30 degrees) in a direction clockwise (opposite to *ACB* arrow) to position +C-A. This means that the A-phase terminal of the Delta is the junction of the (+) end of the "C" coil and the (—) end of the "A" coil, and the associated symbol is:

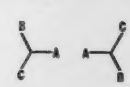


The C- and B-phase terminals follow in order clockwise in Figure 2. C-phase is 120 degrees from A-phase, and B-phase 120 degrees from C-phase. The vector symbols for C- and B-phases are not used.

7—*Star-Star* (use Figure 2)

Requirements: The 2nd Star lags the 1st Star by 180 degrees.

Procedure: From position +A measure an angle of 180 degrees (6 units of 30 degrees) in a direction clockwise (opposite to *ACB* arrow) to position —A. This means that the A-phase terminal of the 2nd Star is the (—) end of "A" coil, and the associated vector symbol is:



The C- and B-phase terminals follow in order clockwise in Figure 2. C-phase is 120 degrees from A-phase, and B-phase 120 degrees from C-phase. The vector symbols for C- and B-phases are not used.

General Information

a. If any two phases are interchanged on both windings, the resultant lag is 360 degrees minus the original lag.

b. If only the phase sequence is changed, the resultant lag is 360 degrees minus the original lag.

c. If any two phases are interchanged on both windings and the phase sequence is changed, the angle of lag is unchanged.

d. The angle of lead is 360 degrees minus the angle of lag.

e. If the connections are fixed, the primary lags the secondary 360 degrees minus the angle the secondary lags the primary. In other words, changing the base changes the angle of lag to 360 degrees minus the original angle of lag.

Method has many uses

1. For *ACB* phase sequence the A-phase terminal is between the A and C coils.

2. If the phase end of one coil of the Star is H_1, then mark (+) the end of a similar coil of the Delta that is nearest the terminal x_1 of the Delta. Mark the opposite end of the same coil (—). Repeat this for all three coils of the Delta. The above is true also if the X_1 is on the Star and the H_1 is on the Delta.

3. If the Star lags the Delta in the problem, then use the following conversion: The angle the Delta lags the Star as shown on the Voltor Diagram is equal to 360 degrees minus the angle the Star lags the Delta. For example, a Star lagging a Delta by 30 degrees is the same as a Delta lagging a Star by 360 degrees minus 30 or 330 degrees.

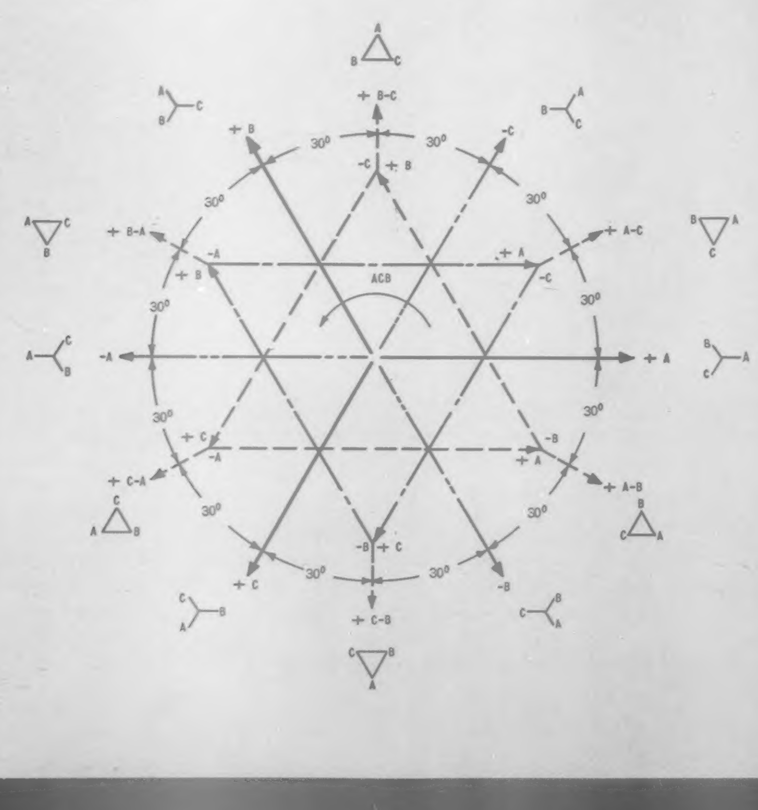
4. For *ACB* phase sequence use the same method as that for *ABC* except that the *ACB* Voltor Diagram in Figure 2 should be used instead of the *ABC* Voltor Diagram in Figure 1. Also, the C- and B-phase terminals of the Delta follow in order clockwise on the *ACB* Voltor Diagram in Figure 2. The C-phase is 120 degrees from the A-phase, and the B-phase is 120 degrees from the C-phase. The vector symbols for the C- and B-phases are not used.

5. If the phase end of the coil of the first Star is H_1, then mark (+) the similar coil end X_1 of the second Star. Mark (—) the other end of the same coil of the second Star. Repeat this for all three coils of the second Star. The above is true also if the X_1 is on the first Star and the H_1 on the second Star.

6. For *ACB* phase sequence use the same method as that for *ABC* except that the *ACB* Voltor Diagram in Figure 2 should be used instead of the *ABC* Voltor Diagram of Figure 1. Also the C- and B- phases of the second Star follow in order clockwise on the *ACB* Voltor Diagram of Figure 2. The C-phase is 120 degrees from A-phase, and B-phase is 120 degrees from C-phase. The vector symbols for C- and B-phases are not used.

7. For *ACB* phase sequence use the same method as that for *ABC* except that the *ACB* Voltor Diagram of Figure 2 should be used instead of the *ABC* Voltor Diagram in Figure 1. Also, the A-phase terminal of the first Delta must be between the A and C coils (+A-C) instead of between the A and B coils (+A-B). This means starting with the (+A-C) on the *ACB* Voltor Diagram of Figure 2 instead of the (+A-B) on the *ABC* Voltor Diagram of Figure 1. The C- and B-phase terminals of the 2nd Delta follow in order clockwise in Figure 2. The C-phase is 120 degrees from A-phase, and the B-phase 120 degrees from the C-phase. The vector symbols for C- and B-phases are not used.

ACB VOLTOR DIAGRAM
VOLTAGE VECTORS FOR
DELTA-DELTA
DELTA-STAR
STAR-STAR
(ACB PHASE SEQUENCE)



VECTOR SYMBOLS	LAG	Aφ	LAG	Aφ	LAG	Aφ
▽ ▽	0°	+ A-C	120°	+ C-B	240°	+ B-A
Y Y		+ A		+ C		+ B
• Y △	30°	+ A-B	150°	+ C-A	270°	+ B-C
▽ △	60°		180°		300°	
Y ⅄		-B		-A		-C
• Y ▽	90°	+ C-B	210°	+ B-A	330°	+ A-C

*DELTA LAGS STAR
(SEE NOTE 3)

(c) E.S. WARNER

FIG 2

REACTANCE

affects Transformer Design

L. W. SCHOENIG
Transformer Section
Allis-Chalmers Mfg. Co.

Impedance has a direct bearing on transformer efficiency, size, cost, and other factors.

THE CONCEPT of transformer reactance has changed materially as the result of the operating experiences obtained since the turn of the century. At one time, power transformers were generally designed with minimum reactance to obtain good regulation since voltage regulators were not available. Also it was not necessary to increase system reactance to limit the fault current handled by circuit breakers.

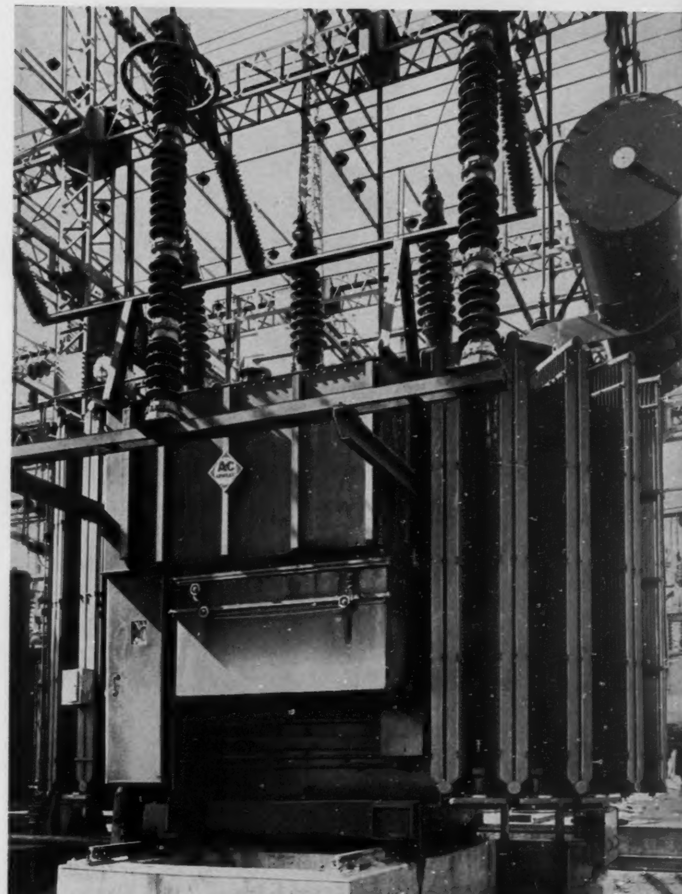
Low reactance is desirable when transformers are of relatively low voltage and small kva rating, such as distribution transformers and especially when systems are small and not extensively interconnected. Most large power transformers today are installed on large and interconnected systems capable of producing large values of fault current, making it necessary to increase system reactance to limit the fault current to values which can be handled safely by circuit breakers. Increased transformer reactance is often an economical method of increasing system reactance.

Another reason for increasing transformer reactance was to make transformers self-protecting in themselves. All transformers built according to NEMA or ASA standards will withstand short circuit currents up to 25 times normal for two seconds. Therefore, the transformer or system reactance should be high enough to limit the short circuit current to this value.

Factors complicate transformer design

Designing a transformer is similar to solving an equation with a large number of variables.

Coordinating the number of turns and coils, coil arrangements, and coil height to obtain specified reactances and losses is one of the most difficult phases of transformer design. Reactance, losses, point of maximum efficiency, exciting current and weights are so related that a change in one will affect the others. It is this factor which annoys transformer designers the most.



LARGE POWER TRANSFORMERS with increased reactance provide an economical means of increasing system reactance. Because this 30,000-kva, 138-kv to 69-kv to 34.5-kv, three-phase transformer interconnects three systems, it required special reactance considerations in its design.

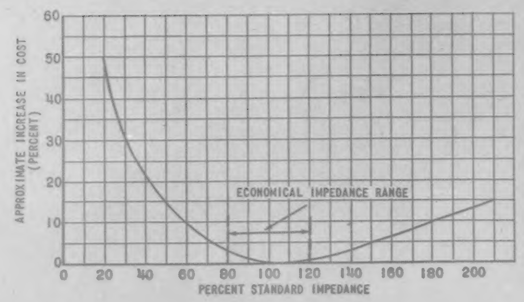
Experience proves that transformers can be economically designed for a rather wide range of reactance. The result of this experience for various voltage classes is tabulated in Table I. As the illustration indicates, transformer reactance increases with the higher voltage classes because of the increased amount of insulation required. It is also for this reason that transformers with high secondary voltages (above 15 kv) usually have reactances which are on the high end of the limits shown in Table I. On the other hand, reactances of

transformers with high voltage windings designed for grounded neutral operation are lower than those given in the following table:

TABLE I

NORMAL TRANSFORMER IMPEDANCES

Voltage Class (HV)	Impedance
15	4.5 — 7
25	5.5 — 8
34.5	6 — 8
46	6.5 — 9
67	7 — 10
92	7.5 — 10.5
115	8 — 12
138	8.5 — 13
161	9 — 14
196	10 — 15
230	11 — 16



TRANSFORMER COSTS, like physical dimensions, are also determined by reactance values. Accompanying illustration plots the approximate increase in cost for non-standard impedance ratings. **(FIGURE 1)**

The decreased amount of insulation possible for this type of design lowers the reactance. For each voltage class there is a value of reactance which will result in minimum transformer cost. Considerable variation from this value is possible without excessive cost increase. Figure 1, which shows variation in transformer cost with reactance, reveals that the cost increase from about 80 to 120 percent is negligible. However, the cost increase becomes appreciable beyond the flat portion of the curve.

Reactance grouping reduces unit size

Usually shell type transformers are designed with two or four reactance groups per phase. A reactance group is a group of high voltage and low voltage coils, high voltage and tertiary voltage coils, or low voltage and tertiary voltage coils, having equal ampere turns and with flux leakage between them. Occasionally, transformers are designed with as much as six reactance groups per phase to obtain a very low reactance. With this arrangement, more interleaving of coils is obtained and, therefore, fewer ampere turns per group. Consequently, total reactance is reduced (see Equation 1). A great many early large shell type transformers were designed this way.

Simple coil arrangements for two and four reactance groups are shown in Figures 2 and 3. No attempt has been made to show the actual number of high and low voltage coils, but only the general grouping. Usually, each phase of the high and low voltage windings requires from 8 to 20 coils each. The exact number depends on the required reactance (the higher the reactance, the more turns and, therefore, more coils), voltage (which determines the total number of turns), volt ampere rating (which determines the ampere rating of the winding and, therefore, the copper cross section), and the number of reactance groups.

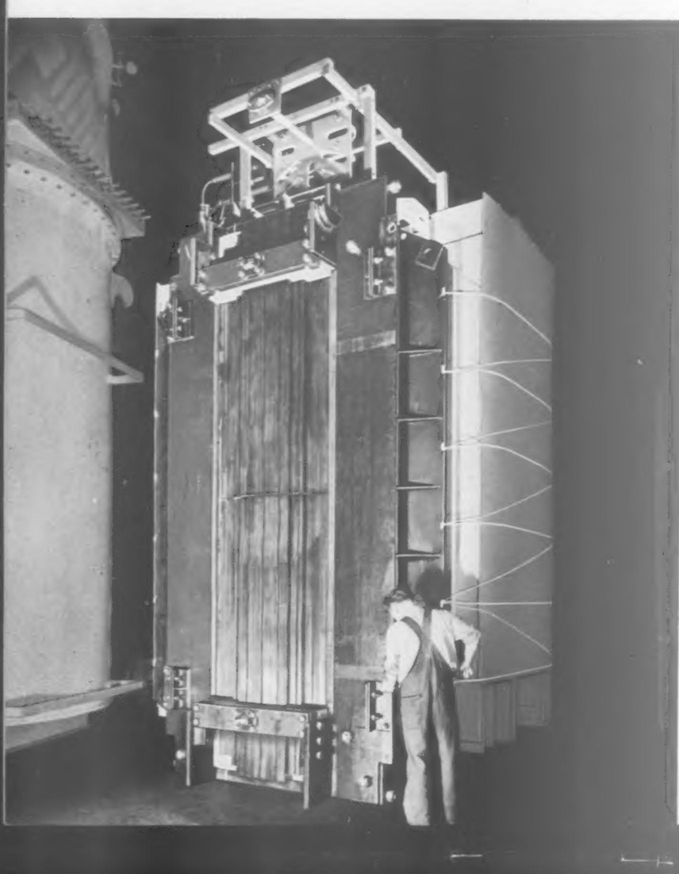
Tertiary coils, if required, are usually located as shown in Figures 2a and 3a. The tertiary voltage coils may, however, be concentrated on one end of the reactance group or more closely interleaved with the high voltage or low voltage, or both, to obtain a rather wide range of reactance from tertiary voltage to high and low voltage.

Transformer characteristics can be varied considerably by changing the reactance grouping. In general, the two reactance group transformers are heavier and have greater overall height. The reactance of any two windings of a transformer may be calculated by Equation 1.

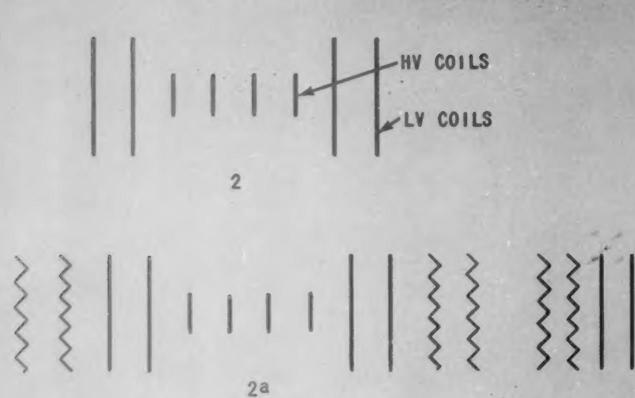
$$\text{Percent Reactance} = \frac{K \times A \times F \times T^2 \times I \times M \times G}{E \times H \times 10^7}$$

Where K=Constant
A=Reactance groups per phase
F=Frequency
T=Turns*
I=Amperes*
E=Voltage per phase*
M=Mean Turn Length of Coils
G=Effective Width of Leakage Path
H=Effective Length of Leakage Path

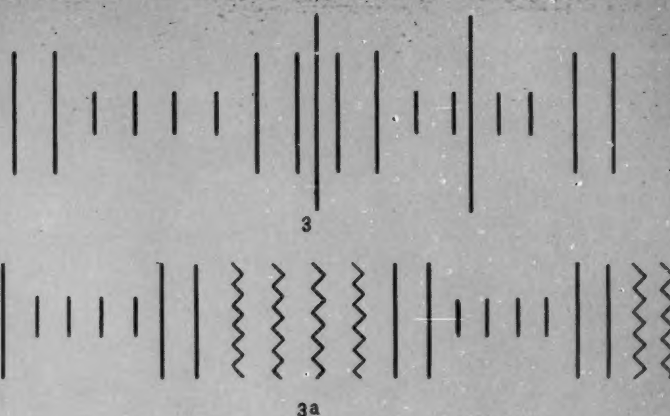
*Based on same winding.



CORE AND COILS assembly for a 40,000-kva, single-phase transformer is designed for normal reactance. Higher than normal reactance would tend to decrease physical size of core and coils. Lower than normal reactance would tend to increase assembly and transformer size correspondingly.



UPPER LINE DRAWING shows the simple coil arrangement for a two reactance group transformer, while the lower shows typical location of tertiary voltage coils when required. **(FIGURES 2 and 2a)**



SIMPLE AND TERTIARY coil arrangement for four reactance group transformers are shown above. These units are usually smaller and lighter than two reactance group transformers. **(FIGURES 3 and 3a)**

As indicated in the formula, the reactance varies as the square of the turns in the reactance group, directly as the frequency, kva load (amperes), width of leakage path, and mean turn of the coils, and indirectly as the voltage and length of leakage path.

Loss ratio affected by reactance

Transformer reactance has a definite bearing on the ratio of losses of a transformer. A short discussion of transformer losses may be helpful in understanding this relationship.

There are two general types of losses in a transformer; no-load loss, frequently called core loss, and load loss, often called copper loss. The no-load loss consists of hysteresis and eddy current in the core iron and I^2R loss in the winding due to the exciting current. The load losses consist of I^2R loss and eddy current loss due to the load current flowing in the windings and stray losses in the tank and core clamping. The no-load loss can be considered constant for all loads, assuming that the voltage applied to the transformer remains unchanged. The load loss, however, varies as the square of the load.

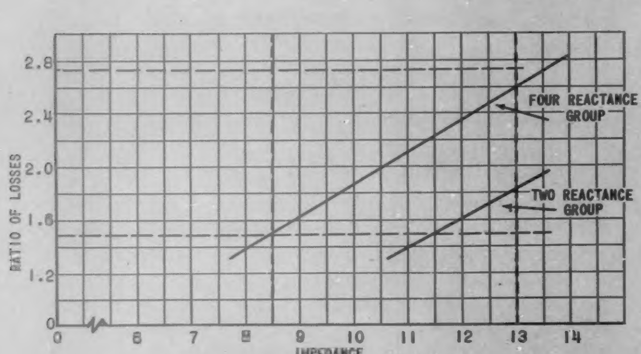
A convenient means of comparing the no-load and load losses is by the ratio of load loss in watts at full load, to the no-load loss in watts. This ratio of losses varies in normal designs from 1.25 to 3.25 for self-cooled and water-cooled transformers, 2.2 to 5.75 for forced air-cooled, and from 2.8 to 6.65 for high capacity forced air-cooled and forced oil-cooled transformer. Table II lists common ratio of losses for various voltage classes and methods of cooling.

TABLE II

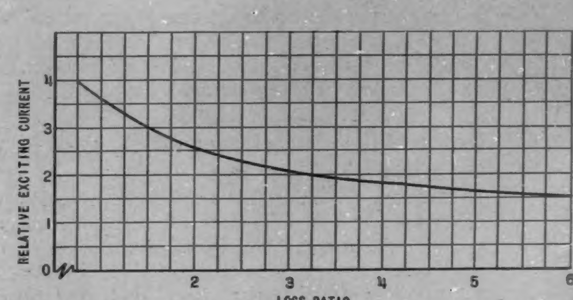
LOSS RATIOS FOR VARIOUS METHODS OF COOLING AND VOLTAGE CLASSES

KV Class	S-C & W-C	FA	FO FA HC
46 and below	1.75 — 3.25	3.1 — 5.75	3.9 — 6.65
69 through 138	1.5 — 2.75	2.65 — 4.9	3.35 — 5.5
161 and above	1.25 — 2.0	2.2 — 3.5	2.8 — 5.0

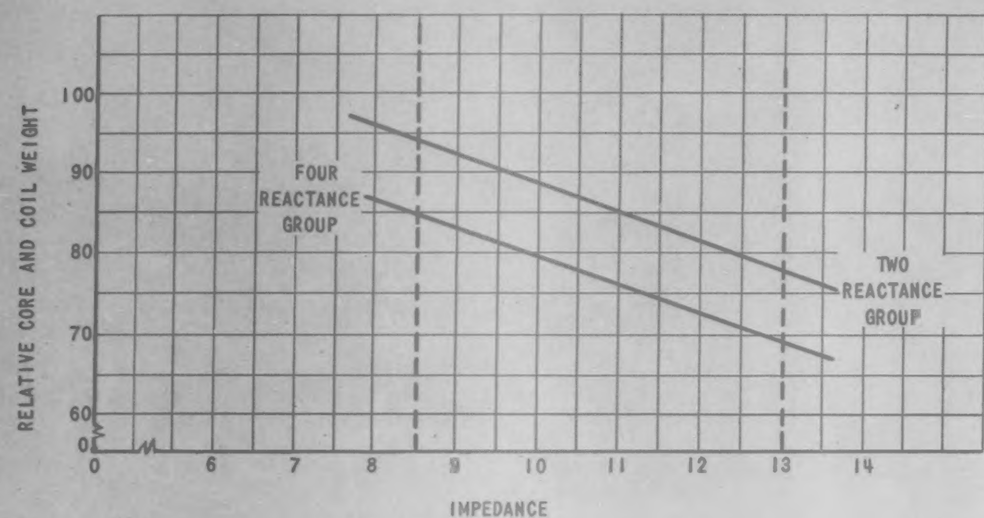
Figure 4 shows the relationship of loss ratio to reactance for two reactance groups and four reactance groups of normal designs for a 30,000-kva, 138-kv, to 13.8-kv, three-phase transformer. The shaded section is the general economical limit of ratio of losses and reactance for 138-kv class transformers. As indicated in Figure 4, the ratio of losses is somewhat higher for the four reactance groups than the two reactance group arrangement. This is true because four reactance group transformers are usually designed with more turns . . . a lower volts-per-turn . . . than the two reactance group transformers. This results in more copper length, and, therefore, more copper loss. A lower volts-per-turn also results in a smaller core cross sec-



COMPARATIVE CHART showing the variation in ratio of losses with impedances for a 30,000-kva, 138 to 13.2-kv, three-phase transformer. Note the difference between two and four reactance groups. **(FIGURE 4)**



CHARTED CURVE shows variation in exciting current with loss ratio for a 30,000-kva, 138 to 13.2-kv, three-phase transformer. Exciting current increases as transformer reactance decreases. **(FIGURE 5)**



GRAPHIC ILLUSTRATION reveals that transformer core and coil weights are influenced by impedance variation. These relative variations are shown for both the two and four reactance group transformers. (FIGURE 6)

tion which means lower core loss. The core cross section is determined from Equation 2.

$$\text{Core Area} = \frac{34.9 \times 10^5 \times V/T}{f \times B}$$

f=Frequency

B=Flux density (lines /CM^2)

V/T=Volts per turn

The equation reveals that the core cross section varies directly as the volts per turn. Also evident is the increase in ratio of losses with higher reactances.

Exciting current which is given much consideration on some power systems has a definite relationship with the core loss and, therefore, the loss ratio, shown in Figure 5. It indicates that the exciting current varies inversely with the loss ratio. This means that a normally designed transformer with relatively high reactance will have low exciting current and, conversely, a transformer with low reactance will have high exciting current.

A variation in reactance not only affects the ratio of losses and exciting current, but also weights. Figure 6 shows the variation in core and coil weight with reactance for both two and four reactance group arrangements.

Determining maximum efficiency

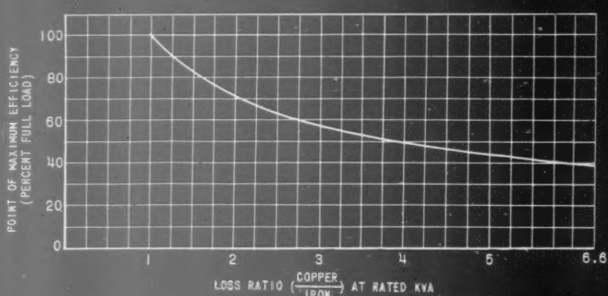
The maximum efficiency of a transformer occurs when the no-load loss and the load loss are equal. Therefore, a transformer with a loss ratio one will have its maximum efficiency at 100 percent load. Figure 7 shows the points of maximum efficiency for various ratios. The load cycle on which a transformer will be operated should be checked very carefully before writing the transformer specifications. The load cycle will dictate the point of maximum efficiency and, therefore, the ratio of losses.

If the transformer will have a high load factor (rather heavily loaded most of the day), a low loss ratio and, consequently, a point of maximum efficiency which occurs as near 100 percent load as possible would be desirable. If the transformer will be lightly loaded or have a low load factor, a higher loss ratio and, therefore, a point of maximum efficiency which occurs at a lower load would be desirable. It is not always possible to design transformers with the exact loss ratio and point of maximum efficiency specified, however it is usually possible to come reasonably close.

The loss ratio has a material effect on the shape of the efficiency curve for a given transformer, but it has little effect on the numerical value of the maximum efficiency for a given amount of material cost. The maximum efficiency of a given transformer is numerically about the same for all ratios of losses with the same loss product, but the point at which it occurs is different for different ratios. Figure 8 compares the efficiency curves and total losses for a 30,000-kva, three phase, 138-kv wye transformer with full insulation and low voltage of 13,800 volts delta, with loss ratios of 1.5 and 2.5.

Efficiency indicates initial cost

An accurate comparison of transformer costs and operating characteristics can be made only by comparing the maximum efficiencies. The principal factor affecting transformer costs is the maximum efficiency. A low efficiency transformer (forced cooled) will have a relatively low initial cost, whereas a high efficiency transformer (self or water cooled) will have a higher initial cost. Comparing transformer efficiencies by comparing the losses at some load (such as full load) is mis-



MAXIMUM EFFICIENCY of a transformer is determined by the load cycle and loss ratio. The above chart shows the points at which maximum efficiency occurs for the various loss ratios. **(FIGURE 7)**

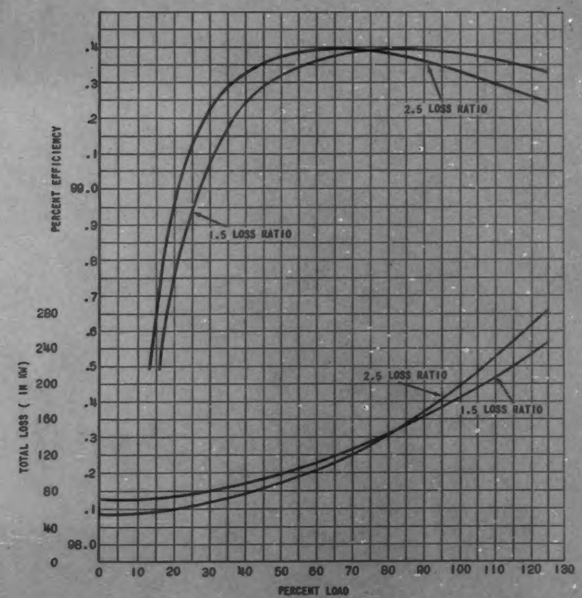
leading because the total losses will be different for various loss ratios. The total losses at a high percentage of full load are higher with a high loss ratio transformer. The transformer in the example has about 10 percent higher total loss at full load with a 2.5 loss ratio than with a 1.5 loss ratio; however, the numerical value of the maximum efficiency is identical.

As shown in reactance Equation 1, the reactance of transformers varies directly as the kva load. This means that transformers which are forced cooled for high capacity will have rather high reactances because, in most cases, the kva rating of the core and coils is increased 50 to 67 percent by these methods of cooling. The impedances tabulated in Table I, which apply to self-cooled and water-cooled transformers, will increase about 60 percent for forced-oil and high capacity forced air-cooled transformers and 33⅓ percent for regular forced air cooling.

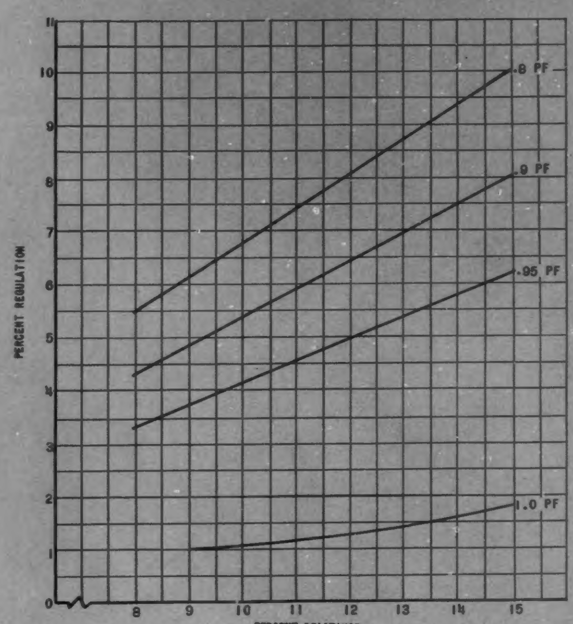
In conclusion

The principal disadvantage of the higher reactance resulting from forced oil and high capacity forced air cooling is the increased regulation or voltage drop through the transformer. This is not so apparent at unity power factor loads, but at 0.8 it is very obvious. Figure 9 shows how the voltage drop or regulation of the usual forced oil or high capacity forced air-cooled transformer varies with reactance and power factor. For reasons of simplicity, it was assumed that the ratio of loss did not change with reactance.

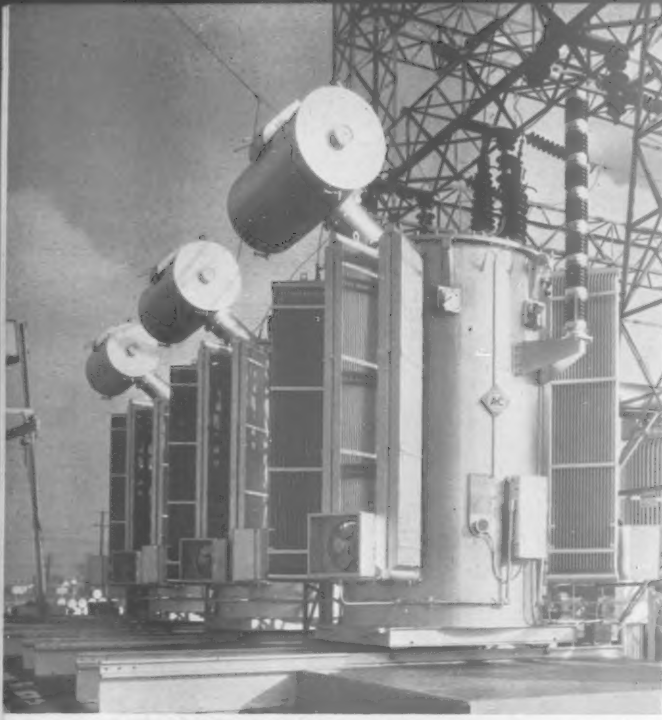
It should be remembered that transformer reactance is not entirely independent of such things as losses, point of maximum efficiency, and exciting current. Low reactance usually means that, relatively speaking, the loss ratio will be low, point of maximum efficiency will occur at a high load, and exciting current will be high. High reactance usually means high loss ratio, point of maximum efficiency at a low load, and low exciting current. It is not economically practical to design transformers with a high reactance and a point of maximum efficiency near full load, or low reactance and low core loss.



DOUBLE CHART compares the point of maximum efficiency and the total losses for a 30,000-kva, 138 to 13.2-kv, three-phase transformer. Maximum efficiency is the same for the 1.5 and 2.5 loss ratios. **(FIGURE 8)**



REACTANCE AFFECTS regulation also, as shown by chart which traces the effects of reactance of a 50,000-kva, 138-kv, three-phase forced oil cooled or high capacity forced air cooled power transformer. **(FIGURE 9)**



FOUR SINGLE-PHASE, 13,333-kva, four-winding transformers are shown installed at a large eastern utility. Winding voltages are 138, 69, 11, and 4 kv. Units were designed to meet special reactances. (FIGURE 10)

Multi-winding transformers

The discussion so far has dealt principally with two winding transformers. When more than two windings are required to supply load the problem of designing transformers for given reactances, losses, etc., becomes considerably more complicated. There is practically no flexibility in a design when all reactances are specified. Normal reactances for three or more winding transformers present no particular design problem, however, unusual reactance relationships often require complicated and uneconomical designs. Unless system characteristics require specific reactances, care should be exercised in specifying reactances as the transformer cost may be materially increased.

The 40,000-kva bank of single-phase 138-kv, 69-kv, 11-kv, 4-kv four-winding transformers shown in Figure 10 is an example of transformers designed for special reactances. These transformers are used to tie together four parts of an eastern utility power system. A system study indicated that to insure proper system operation and load distribution it was necessary to design the transformer to meet rather special reactances. These reactances on a 13,333-kva base, are shown in the following table.

REACTANCES OF SPECIAL GROUP OF 13,333-KVA, 138-69-11-4-KV SINGLE-PHASE TRANSFORMERS.

Windings (Kv)	Per Cent Reactance
138 to 69 —	12.9
138 to 11 —	8.4
138 to 4 —	23.4
69 to 11 —	23.6
69 to 4 —	8.28
11 to 4 —	34.0

The reactances were obtained by using a modified two-reactance group coil arrangement. The flexibility of the coil arrangement with the shell type construction aided in obtaining these reactances.

New Products

New Pole-Type Voltage Regulator

Development of a new low-priced pole-mounted regulator has just been announced. The unit is designed especially for REA and private utilities serving rural, small town and suburban loads. The introduction of the new step-type regulator, to be known as the JFR, means that rural and outlying customers will now have the same quality of voltage regulation provided by any type of regulator available today.

The regulator is the result of studies that began before the war, which showed that, with the expected increase in loads, maintaining reasonable voltage control on rural lines would be a serious problem unless some new economical method of voltage regulation was made available to the power companies serving rural consumers. The first test models of the new regulator were installed in 1944. Since that time a number of other units have been installed and have performed with complete satisfaction in various parts of the country under varying weather conditions.

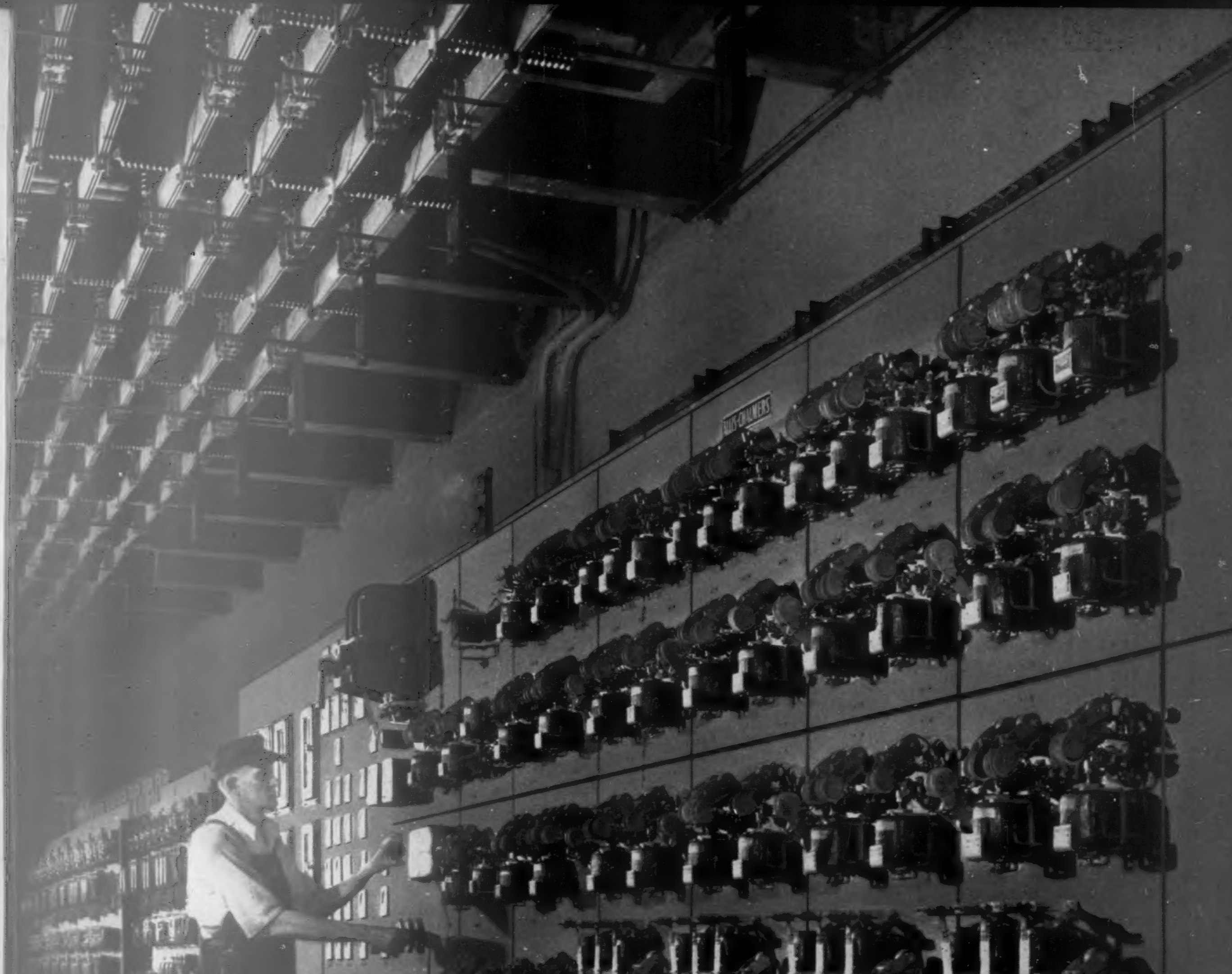
The regulator utilizes the same principle of operation as the larger step-type station voltage regulators that have become increasingly popular since they were developed 16 years ago. The unit provides full ±10% regulation in 32⅝% steps. The autotransformers, tap changing mechanism, potential, current and control transformers are all oil-immersed in a tank similar in design to a standard distribution transformer. The control is housed in a smaller cylindrical tank having a cover that is easily removed for test or adjustment, yet sealed from dust and moisture.

The control panel has all the essential functions of the larger regulators: a voltage control relay, voltage integrator switch, reactance and resistance line drop compensators, voltage level adjustments, test terminals and fuse protection.

Initial production will be made only in the 10.8 kva, 7200 volt, 15 amp size, expanding later into other ratings. Full scale production will be reached late this summer.

Because the extended use of regulating equipment in outlying areas calls for lower cost equipment, every effort has been made to reduce frills in manufacture. The new unit costs less than any regulator of any type available today.

MORE FACTS about new equipment listed here can be obtained by writing the Allis-Chalmers ELECTRICAL REVIEW, Milwaukee 1, Wisconsin.



CONTROL SWITCHBOARD for controlling currents operating a four-stand tandem cold mill in a large mid-western steel plant is based on individual motor-per-generator scheme.

THIRTY YEARS
of Automatic Reclosing

C. L. HEADLEY
Superintendent, Relay Department
Consolidated Gas Electric
Light & Power Company of Baltimore
Baltimore, Maryland

Faster reclosing means added system protection, more reliable service, utility experience shows.

AS EARLY as 1914, it was observed that the great majority of times when the oil circuit breaker of an overhead circuit tripped because of fault current, the fault was cleared and the service restored when the breaker was reclosed. This observation gave rise to the idea of reclosing the oil circuit breaker automatically to restore service more quickly.

Our first method of automatic reclosing was arranged to effect immediate reclosures following the first two immediate trip-outs and lock-out on the third immediate trip-out. It was designed for use only on circuits equipped with instantaneous overcurrent tripping relays and was installed on the majority of our 4,150-volt feeders. This scheme operated successfully for many years by expediting the restoration of service to our customers. Records of the operations of this type of relaying show that service was restored by automatic reclosing approximately 75 percent of the times the breaker tripped out because of fault current.

Inverse time relays added

By 1930 our system had grown considerably; the distribution feeder loads had increased; higher rated fuses had been installed in the taps; and the feeders had become more complicated by the increased number of fused taps. It then became apparent that the original method of relay protection was not wholly adequate. Feeder faults occurred that should have been cleared by fuses; but because of the fast operation of the overcurrent relays, the feeder breaker at the station frequently tripped three times and locked out before the fuse could blow. Furthermore, after the breaker had tripped and locked out and the fault was cleared, we occasionally experienced difficulty when attempting to restore the feeder to service. This difficulty was experienced because the inrush current, resulting from picking up cold loads, was in itself of sufficient magnitude to operate the relays and to trip the feeder breaker.

A revised method of relaying was therefore necessary to facilitate coordination between the station breaker and the feeder fuses and to provide for picking up cold loads when energizing a feeder. To attain the required protection, inverse-type overcurrent relays equipped with instantaneous-tripping attachments were used. The inverse-time relays were adjusted to coordinate with the feeder fuses; the instantaneous-trip attachments were set to operate only on high values of current for quickly clearing faults near the station bus. These relays operated on phase overcurrent and were used successfully for a number of years. The application of this new type of relaying made it necessary to change the type of automatic reclosing. The new scheme provides for one reclosure after the first trip-out followed by lock-out if the second trip-out occurs within a predetermined time (approximately 30 seconds). A slight time delay of one-fourth to one-half second after the first trip-out is allowed before energizing the relay to close the oil circuit breaker. This time interval permits the overcurrent tripping relays to reset and gives the ionized air at the point of fault a chance to dissipate.

By 1943, the majority of our 4150-volt feeders were equipped with this type of relaying. Records taken over a period of years showed the following results:

1. The number of trip-outs had been considerably reduced;
2. The number of fuses blown had been increased;
3. The number of service restorations by automatic reclosing was approximately 55 percent. (This loss of 20 percent is caused primarily by the longer fault clearing times, resulting from the use of inverse-time relays.)
4. No difficulty with relay operation had been experienced from inrush current when energizing a feeder, if the normal load on the feeder was not more than 75 percent of the relay setting.

It will be noted that with this type of relaying the percentage of service restorations has been reduced. This reduction is due mainly to the time delay action of the protective relays. Occasionally, a fault results into permanent trouble because it is not cleared as quickly as with our first scheme.

Multiple reclosures not recommended

Experience shows that with the abovementioned type of relaying only a very small percentage increase in service restorations can be realized if a two- or three-shot reclosing relay is used. A second automatic reclosure averages about eight percent increase in service restorations, and only about two percent to three percent increase is realized with a third reclosure. Another discovery is that if more than one automatic reclosure is required to clear a fault when the fuses and relays are correctly coordinated, the fault is usually on the main portion of the feeder and must be burned clear. Repeated reclosures increase the damage caused by permanent faults and may result in line burndowns, in which case no service will be restored even though the oil circuit breaker finally remains closed. For this reason, and because of the increased stress on the station equipment and the additional shocks to the system, it was felt that more than one automatic reclosure is not justified.

Most of the 33,000-volt and 110,000-volt circuits, as well as a few of the 13,200-volt overhead circuits, are equipped for one automatic reclosure. Records covering the operation

of transmission circuits on our system for the past twelve years show that 96 percent of the faults occurring on 110-kv circuits have been cleared by the first trip-out and that service has been restored by one automatic reclosure; 84 percent of the faults occurring on 33-kv circuits and 78 percent on 13-kv circuits have likewise been cleared. High-voltage circuits are conducted through cleared right of ways to prevent faults caused by falling tree limbs or other obstructions. It is felt that this factor largely accounts for the higher percentage of service restorations on these circuits, as compared with 4,150-volt feeders. Even though a portion of the 4,150-volt service is supplied by underground cables, faults on these cables account for less than two percent of the total troubles occurring on the 4,150-volt system.

Although we had experienced a high degree of service protection and a good percentage of service restoration by use of the foregoing methods of relaying, it was felt that some faults resulted in permanent troubles because they were not cleared quickly enough. We also believe than many fuses on our 4,150-volt system were blown by faults of a temporary nature. If such faults could be cleared by tripping the feeder breaker before the fuse operates, the service would be immediately restored by automatic reclosing and customers would experience only a momentary outage.

Initial quick-trip relaying method

The latter idea was conceived years ago and about 1935 a relaying method was developed which has resulted in improvement to the service. This relaying method is designed to trip the breaker by high-speed relays on the majority of initial faults on the feeder. The breaker is then automatically reclosed; and if the fault is not cleared when the breaker is reclosed, the second trip-out is initiated by inverse-time relays. When the second trip-out occurs, the fault is considered permanent and no further automatic reclosure is initiated. The high-speed tripping on the initial fault provides quick clearing to minimize the amount of damage that might be caused by the fault and generally prevents the unnecessary blowing of fuses located between the breaker and the point of fault. The time-delay tripping on the second immediate trip-out, however, provides coordination between the station breaker and the feeder fuses.

This method of quick-trip on the initial fault and time delay for the second immediate trip-out was tested during 1936 and 1937 by applying it to two of our 4,150-volt feeders for testing purposes. Records on these feeders covering a number of years show that over 80 percent of the times when the oil circuit breakers tripped because of fault current, the service was restored by automatic reclosing. On those occasions when the oil circuit breakers tripped twice, and locked out, permanent troubles were found. Records also indicate that this method of relaying offers the following advantages:

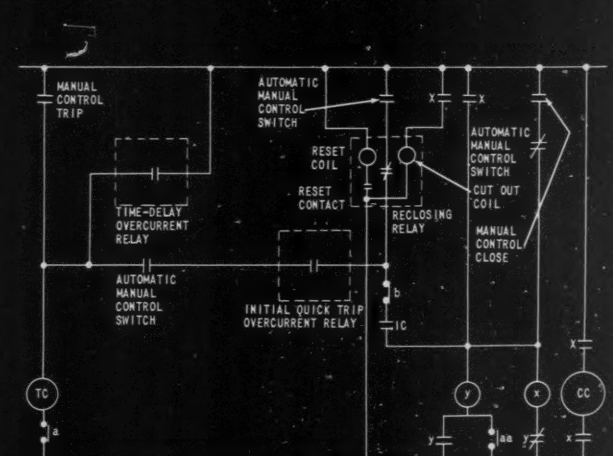
1. Clears all temporary faults in minimum time, thereby reducing system disturbances and damage to equipment.
2. Increases the percentage of service restoration by automatic reclosing.
3. Reduces the number of line fuses blown by temporary faults, thereby reducing the number of prolonged outages to customers as well as fuse cost.
4. The reduction of customer outages results in a considerable saving of labor in line patrolling and helps in promoting customer good will.
5. Reduces the possibility of line burndown, thereby reducing the hazards to the public.

The schematic shown is a typical diagram of the method we use to obtain quick trip on the initial fault, automatic reclosing, and time delay on the second immediate trip-out.

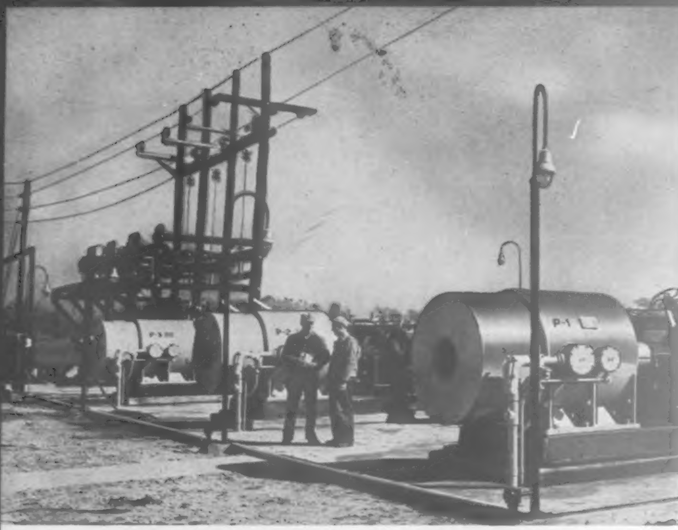
When a fault occurs upon the feeder, the inverse time overcurrent relay starts to operate. However, the high speed overcurrent relay operates instantaneous to trip out the breaker. This high speed relay is blocked out of action by condenser P which, when charged, reduces the flow of current through coil E to practically zero. The breaker then recloses by means of the reclosing relay. If the fault is not cleared due to the opening of the breaker, the inverse time overcurrent relay continues to operate and trips the breaker again. The high speed overcurrent relay will function only after the first time, when sufficient time has elapsed for condenser P to discharge through resistor R. Our practice is to use only one reclosure and adjust the time of the inverse time overcurrent relay so that, if the fault is on a fused feeder, the fuse will clear the fault after the breaker recloses. Of course, if the fault is between the circuit breaker and the fuse, the breaker will open and remain open.

During 1947 we installed metal-clad switchgear on all the 4,150-volt feeders in two of our major 4-kv indoor substations. As the result of our previous experience, this switchgear is equipped with instantaneous relays to initiate quick tripping on the initial fault, automatic reclosing, and inverse-time relays to initiate the second immediate trip-out. Ground relays, in addition to phase relays, are used on this equipment and they provide quick tripping on the initial phase to ground fault and inverse time on the second immediate trip-out. We have not had sufficient experience with these installations to record the amount of improvement that will be gained. Our plans are to equip the majority of our 4,150-volt feeders with this method of protection. We are also applying this method of protection on our high-voltage circuits.

Thirty years of experience with reclosing relays supports the claim that automatic reclosing definitely improves the reliability of service, especially when it is utilized in unattended substations. Furthermore, the greatest improvement to system protection and to continuity of service for the customer is realized when this automatic reclosing is preceded by high-speed tripping.



METHOD OF APPLYING INITIAL QUICK TRIP AND AUTOMATIC RECLOSING



EXPLOSION-PROOF MOTOR design for hazardous applications embodies advances which minimize maintenance. Made to pump 7,000 gallons of crude oil per minute, these 600-hp motors are built to operate efficiently at all times and to resist injury when exposed to year-round weather.

Care of AC Rotating Equipment

PART II OF IV PARTS

FRASER JEFFREY
Assistant to the Chief Electrical Engineer
Allis-Chalmers Mfg. Co.

Proper application prolongs machine life and efficiency and minimizes maintenance and repair.

OVERLOADING must be regarded as a serious maintenance consideration since it has a definite effect on the life of electrical machine insulation.

Because a motor is old does not necessarily imply that, in all probability, it is a very liberally built machine able to carry overloads. Even if a thermometer is placed in a spot where the most nearly representative temperatures are to be expected and it shows somewhat lower than rated rise, there is no reason for concluding that the machine can handle more than its nameplate rating. It may or may not have excess capacity. If in doubt, the only practical resource is to consult the manufacturer.

Bigger loads need larger motors

Some years ago a 4,000-hp slip ring induction motor was operating in a steel mill where the peak loads were gradually stepped-up until the machine was carrying recurrent intermittent maximum peak loads of 14,000 hp, or three and one-half times its normal load rating. Under this loading condition, the motor temperature was low, something under 40 degrees C rise, but the solder in the rotor clips could not be maintained due to the high localized heating in this particular part of the machine which was never designed for such extremely high overload conditions in the first place.

The motor was finally replaced by a 6,000-hp motor with rotor clips which were specially designed to meet the high recurrent peak load conditions required. The extra horsepower was needed for an increased overloading schedule. This particular case shows that ordinary electrical equipment is not always built like the one-horse shay in which all the finely designed and assembled parts broke down simultaneously.

Electrical equipment cannot always be judged from its temperature limits alone, but like a chain, from the weakest link in its structure. Such conditions may be due to limita-

Vibration*

Accidental single-phase operation of polyphase motors, off-center rotor with uneven air gaps, excessive bearing clearance, improper motor alignment, shifted balance weights and bent shafts cause vibration. Very often, vibrations are transmitted to electrical machines from the driven apparatus and, in many cases, can cause the rotor to rub against the stator, shorting laminations, cause localized hot spots and adjacent insulation damage, or even failure. Machine vibration should be investigated immediately before serious consequences are brought to bear.

Uneven air gap

Equation 7 presents an indication of the relative unbalanced pull in pounds due to an uneven air gap with an off-center rotor. Unbalanced magnetic pull in pounds

$$= \frac{2.76 \times G_d \times (G_D)^2 \times P_A \times 10^{-8}}{2}$$

where G_d = air gap displacement in percent divided by 100.

†G_D = air gap peak flux density in lines per sq. inch.

P_A = For synchronous machines, pole arc in inches × ½ number of poles × active axial length of pole iron in inches.

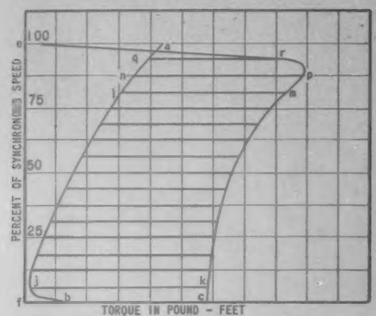
P_A = For induction machines, ½ the circumferences of inside diameter of stator iron × the actual axial length of stator core iron.

A good example is a 600-hp slip ring type induction motor with a normal single air gap of .055 inches. Assume a 25 percent displacement of this air gap where G_D = .25. The gap density = 40,400 lines per square inch, and the pole face area involved, P_A = 1,410 square inches. The unbalanced magnetic pull in pounds from the above equation equals 7,940 pounds.

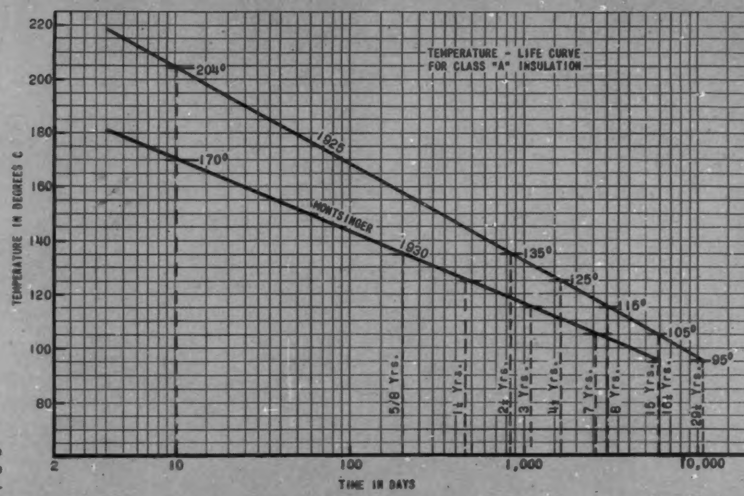
Since the actual weight of the rotor including the shaft of this machine is 3,150 pounds, the pull due to an uneven air gap, with 25 percent displacement, is much greater than the weight of the rotating part itself. The greater the displacement, the greater the unbalanced magnetic pull becomes.

*This mention of vibration and uneven air gap is an addition to Part I, ELECTRICAL REVIEW, *First Quarter, 1949.*

†The air gap peak flux density varies for different types of machines from 40,000 to 45,000 and sometimes as high as 50,000 to 55,000 lines per sq. inch.



MOTOR TORQUE available for acceleration can be determined by the "averaging" method shown in this torque-speed chart. Curves indicate power needed for acceleration as well as driving the load. **(FIGURE 9)**



CLASS "A" INSULATION life can be estimated by these commonly used temperature-life curves. Both the 10-degree (upper) and 8-degree (lower) curves are subject to conflicting opinions as to which is more accurate. **(FIG. 10)**

tions in mechanical parts, slip rings, brush capacity, cable conditions, torque and current requirements, etc.

Starting poses heat problem

It is not often recognized that in a squirrel cage induction motor the kinetic energy of accelerating its own rotor as well as the rotor of the driven machine, and any load it may be carrying is dissipated in the form of heat in the rotor bars and the rotor end rings of such a machine. This differs from the slip ring induction motor where this accelerating heat dissipation occurs in an external starting resistance in the rotor circuit. Therefore, squirrel cage induction motor trouble, due to overheating of the rotor bars which causes their cracking and sometimes cracks end rings, may not be a maintenance problem, but one of application. In other words, the rebuilding in duplicate of a part of a machine that has given trouble may not necessarily remedy the difficulty if fundamental application conditions were wrong in the first place.

The temperature-time constant of a squirrel cage induction motor during the starting period must be seriously considered if the driven machine has large inertia or flywheel effect. Starting time in seconds can be actually calculated from Equation 8:

$$t = \frac{WR^2 \times S}{306 \times T}$$

Where t = Starting time in seconds

WR^2 = WR^2 of driven machine + WR^2 of the rotor of the motor — (both in terms of motor rpm)

S = Motor rpm at full load speed

T = Available motor torque in pound-feet for acceleration of the load

To find the available motor torque "T" for acceleration, it is necessary to integrate, or average out, the difference between the torque required to drive the load and the total motor torque available over the entire starting period. A convenient way of determining "T" for acceleration is illustrated in Figure 9, showing the speed-torque curve of a single-speed motor superimposed on the speed-torque curve of a blower that is not unloaded during the starting period. This assumes no drop in line voltage during the starting period. The area enclosed by a, b, c, m, p, and r represents the power required for acceleration, while the area enclosed by a, e, f, b, g, n, and q represents the power required to drive the load.

A quick method of obtaining the "average" torque T_a or T, available for acceleration, assuming no potential drop at motor terminals during the starting period, can be derived from equation 9:

$$T_a = \frac{bc + jk + \text{------} lm + np + qr}{n}$$

Where T_a = "Average" torque in pound-feet available for acceleration, assuming no potential drop

n = Total number of abscissae, such as bc, jk, etc., considered

bc, jk, etc. = Value of motor torque in pound-feet from speed torque curve, Figure 9

Under line-starting conditions, the current may vary from 450 to 600 percent or more of the full-load current and hangs on until the motor is practically up to full speed. Heating of the motor, especially at the lower speeds, is very rapid. Consequently, the starting time and the motor design must be such that dangerous temperatures are not reached.

If the potential of the power supply drops during the starting period, the time of acceleration is also lengthened, another factor which must be seriously considered. Another important consideration is that the power supply system has the necessary regulation and capacity to maintain the voltage at or very near normal value during more than normal load demands.

Driven equipment affects starting-time

For line-starting squirrel cage induction motors driving centrifugal pumps and fans that are *not* unloaded during the starting period, the time "t" may vary from 3 to 5 seconds while for high-speed, high-inertia blowers which are *unloaded* during the starting period, "t" may vary from 40 to 50 seconds. Certain types of coal pulverizers also require from 30 to 50 seconds for acceleration, and other high-inertia loads may require still longer periods of time.

However, when "t" is large, 15 to 30 seconds or more, the design of the motor must be such that the "mass" of copper and other materials in both the stator winding and the cage winding of the rotor are able to absorb and dissipate the heat loss, without exceeding safe temperatures.

Starting periods varying from 3 to 15 seconds might be considered normal, 15 to 30 seconds as abnormal, and 30 to 50 seconds as very special cases. The starting time "t" may be shortened by increasing "T" which, ordinarily, would mean the use of a still larger motor with an even greater starting current. When "t" exceeds 50 seconds, a clutch, or another type of motor, such as a slip ring induction motor, will have to be considered. These motors have the ability to exert large starting torques with minimum starting currents and, as such, have almost unlimited temperature-time constants. The WR^2 of the rotor of the driving motor must also be considered in all such cases of acceleration.

Heat cuts life of class "A" insulation

Overloading reduces the life of Class "A" insulation, as shown in the two life curves in Figure 10. The upper was established about 1925 and represents the life of Class "A" insulation in air. It is often referred to as the 10 degree life curve because insulation life is approximately halved by each 10 degree increase in temperature. The lower curve was established about 1930 by tests of insulation immersed in oil. This curve is sometimes called the eight degree curve for a similar reason.

There are still differences of opinion as to which of these curves should be used because insulation life can be gauged by so many different methods, such as:

A. *Electrical methods*
   1. Insulation resistance
   2. Electric breakdown
   3. Power factor
   4. Dielectric loss

B. *Mechanical limits*
   1. Physical conditions by observation
   2. Cracking and bending on various sizes of radius
   3. Flexibility
   4. Tensile strength
   5. Folding endurance

Slight traces of acid in the oil greatly affect the life of Class "A" insulation,[1] which is represented as a band in Figure 11. The heavy, straight line through the approximate center of the band provides a definite yardstick from which to gauge insulation life and shows the maximum and minimum limits of insulation life which might be expected under various temperatures. At 105 degrees C, the insulation life varies from 8½ to 23 years, with the solid line within the band showing a life of 15 years. Note, too, that the 105 degrees C is the total limiting temperature for Class "A" insulation as set up by the AIEE Standards.

Close observation of the solid or heavy line curve indicates that if a temperature of 95 degrees C is maintained for a period of 29.2 years, the Class "A" insulation will, theoretically, reach the end of its usefulness and will be subject to failure under mechanical or electrical shock. At 105 degrees C, the value drops to 15 years. As previously stated, each 10 degree rise in temperature reduces insulation life by approximately 50 percent.

The illustration shows that machines operating at 40 degrees C rise by the thermometer method in an ambient of 40 degrees C and a hot spot of 15 degrees C as set up in the AIEE Standards,[2] thus having a total limiting temperature of 95 degrees C, would have a life expectancy of 29.2 years. However, if the rating were increased until the total limiting temperature was 115 degrees C, then the insulation life would be reduced to eight years, or about one-fourth of ordinarily expected life.

Theory helps, operation determines life

While these values are theoretical, such life curves enable reasonable estimates to be made of the life span of Class "A" insulation. The relation between the life expectancy of insulation indicated by laboratory and field tests, and the life of insulation of any given machine, is in itself an estimate. Use of such information must be tempered by good judgment based on operating experience.

Naturally, very few machines operate continuously at their maximum rated temperatures so that the life expectancy of insulation operating at lower temperatures may be extended considerably.

Undoubtedly, there are electrical machines that have been in more or less continuous operation for long periods of time. Some are known to have been operated for 25, 30 or 40 years, with many of them still in operation.

It is obvious, however, that in figuring depreciation so that the investment can be amortized in a reasonable period of time, it is very doubtful whether it would be considered good business to use 40 years. The most practical maximum for obsolescence and replacement is 15 or 20 years.

Bonding material determines class "B" span

There is no similar life curve data available for Class "B" materials. Today, it is assumed that the life span of a winding with Class "B" insulation is greater at Class "A" temperature rises than at Class "B" temperature rises. While Class "B" materials are not appreciably susceptible to deterioration from the high order of temperatures encountered in some service conditions, *the bonding materials* used in them are greatly affected. Deterioration of this bonding material has considerable influence on the life expectancy of Class "B" insulation.

A word or two about painting

Painting may seem insignificant when associated with electrical equipment. Yet experiences from several sources recommend a more serious approach to it.

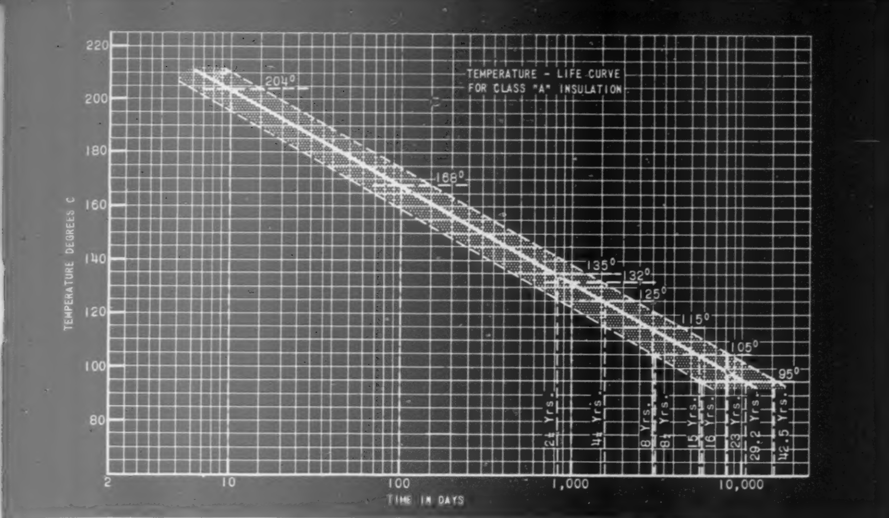
Lead or zinc paints should not be used to paint the inside of machines, since there may be a possibility of metalizing some of the insulated parts and creepage surfaces. Air-drying insulating varnish should be used instead.

Paint shorts bearing housing insulation

Bearing pedestal and bearing housing insulation, if it is used, should not be painted over when repainting machines, lest it

[1]Effects discussed in detail in the Proceedings of the Midwest Power Conference, held in the summer of 1944, in Chicago, Ill. (Volume VII).

[2]General Principles upon Which Temperature Limits are Based in the Rating of Electrical Machinery and Apparatus, AIEE, Number 1, June, 1947.



MAXIMUM AND MINIMUM limits of class "A" insulation are shown under various temperature conditions. Straight line through the approximate center of the band provides a definite measure of insulation life. **(FIGURE 11)**

be short circuited. This insulation is used to prevent shaft-to-bearing currents which are present mostly in the larger machines. Bearing housing or pedestal insulation, when used, is usually painted at the factory with a non-conducting red color to denote its importance. Frequently, a small plate with a statement regarding bearing insulation is placed on the motor. If the bearing insulation has been painted over, the short circuit should be removed immediately and that part of the shaft which runs in the bearing babbitt should be inspected for any roughness or pitting which may have been caused by shaft currents. Increasing darkness in the color of the bearing oil may be an indication of shaft currents.

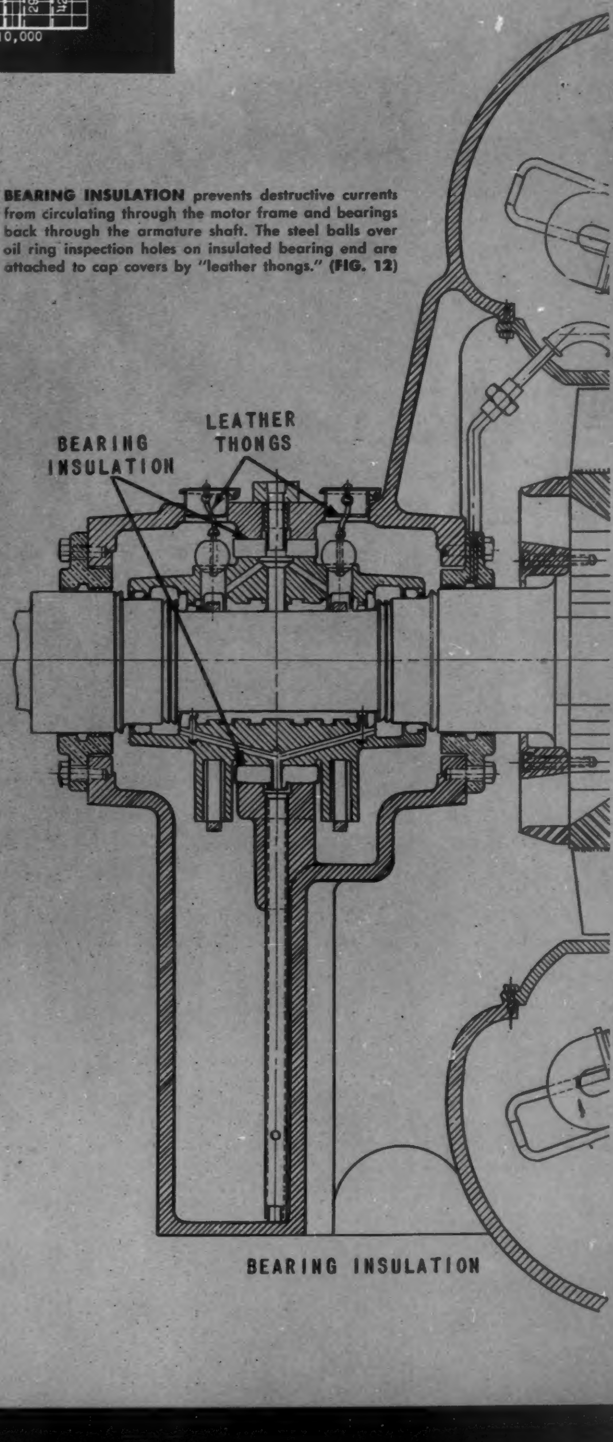
Occasionally, bearing insulation is placed inside the bearing bushing itself (Figure 12). Normal painting of exterior parts of the machine would not affect the insulation. Insulated bearings have leather thongs hanging from the caps covering the inspection opening on top of the bearing. The other ends of the thongs are fastened to steel balls covering the oil ring inspection holes inside the bearing shell. Metal chains instead of leather thongs may be found on the other end of the motor. Some maintenance departments fail to recognize the importance of these leather thongs and have replaced them with conducting material, thinking that the factory had made a mistake. In many instances where such replacements were made, machine shafts and bearings were damaged by shaft currents.

In conclusion, mind load limits

Today's production race encourages the tendency to load beyond safe limits equipment which, according to statistics, is old. Oftentimes it is absolutely necessary to get the most out of existing machines, many of which usually run on a full 24-hour schedule. In spite of the best efforts to attend to the details of machine upkeep, breakdowns and consequent interruptions in production are apt to occur. Immediate repairs or replacements of parts or the entire machine must be made by the maintenance department.

The maintenance department can be likened to a fire department. A certain amount of equipment, sometimes quite expensive, must be kept available for instant use for motor upkeep and repair. Moreover, the equipment must be in good condition so that job can be done quickly by a staff able to analyze and interpret cause effects which might prevent future failures.

BEARING INSULATION prevents destructive currents from circulating through the motor frame and bearings back through the armature shaft. The steel balls over oil ring inspection holes on insulated bearing end are attached to cap covers by "leather thongs." **(FIG. 12)**



Fundamentals of AC

PART V OF VI PARTS

DR. ERWIN SALZER
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Air blast breakers are unique in that prestored air under pressure serves as an arc extinguishing and operating medium.

IN AC CIRCUIT interruption a vulnerable arc is first drawn in a gaseous medium, and then the arc path is deionized during a zero pause of the current wave at a sufficiently rapid rate to preclude reignition of the arc after the zero pause. The three general classes of circuit breakers, air, air blast, and oil, are named for the interrupting media which play an important part in the interrupting process. For each class there are combinations of interrupting principles which lend themselves particularly well to the conditions determined by the particular medium used, as exemplified by the arc chute of the air magnetic breaker discussed in the previous installment.

Dawn of air blast principle

Flames and arcs are of a similar nature, both consisting of hot, ionized gases.

Our forefathers used to extinguish flames of candles and lamps by blowing jets of air against the flames. In modern air blast breakers, compressed air stored in a tank and released through a nozzle to form a high velocity jet is used as the arc-extinguishing means.

Fluid mechanics used in breaker design

Since air blast breakers are predicated upon the action of jets of a fluid, i.e. of air, their design involves many principles and problems of fluid mechanics.

WE hope that many of our readers have been following this series of Dr. Salzer's, which will be concluded in the next issue. We believe that it is one of the most comprehensive treatises written in recent years on the broad field of circuit interruption, including breaker theory, design and application.

Requests from engineers, laboratories, manufacturers, libraries, and universities have depleted our supplies of the Third Quarter, 1948 ELECTRICAL REVIEW, containing Part II of the series. To make sure that each reader may have a complete set of all installments, the entire series will be reprinted in book form during the latter part of this year. Watch future issues of the REVIEW for the announcement.

— Editor's Note

The basic parts of an air blast breaker are the compressed air storage tank, the blast valve controlling the escape of the blast from the tank, the arcing chamber where arc extinction is effected, the insulating blast tube for conducting the blast from the tank to the arcing chamber, and the combination of muffler and silencer which, in addition to reducing the temperature of the arc products leaving the arcing chamber before permitting their escape to atmosphere, operates as an acoustic filter.

One of the most important parts of the arcing chamber is the zone of restricted cross-sectional area where the potential energy inherent in compressed air is converted into the kinetic energy of the arc-extinguishing blast. The portion of the breaker which converts air pressure into air velocity operates as a pneumatic transformer.

In normally designed air blast breakers the air tank is at ground potential and the arcing chamber at an elevated potential. Hence the length required for the insulating blast tube interconnecting the tank and the arcing chamber depends upon the difference of potential between ground and arcing chamber. Breakers for very high voltages require blast tubes of considerable length. The longer the blast tube, the longer the time required for the blast to flow from the tank to the arcing chamber. This is an important factor because it affects the speed at which a fault can be cleared by the breaker.

The blast valve is usually arranged immediately adjacent the breaker tank and at ground potential. Since breakers for very high voltages require long blast tubes, there may be considerable expansion of air within their blast tubes, resulting in considerable loss of pressure at the point or points of break.

Where an air blast breaker comprises a plurality of pole units supplied with compressed air from a common breaker tank, the design must ensure substantially equal pressure distribution to all pole units.

A bend at any point of a blast conduit tends to reduce the speed of pressure build-up and should be avoided where rapid build-up of pressure is required.

Interruption of circuits at relatively high voltages may require use of superposed multibreaks in series. In such breakers the build-up of pressure at all points of break should be equalized as well as possible before the contacts are allowed to part.

Glimpse into aerodynamics

Though the behavior of liquids and gases is the same and both are governed by the same laws, their differences become significant at high flow velocities. Liquids are incompressible while gases are compressible. So long as the velocity of a flow of air is small in comparison to the velocity of sound in air, which is 1,115 ft./sec. at normal temperature, air may be considered incompressible. Since the velocity of the blast in air blast breakers is generally in the order of sonic velocity we must generally apply the laws which govern specifically the flow of gases at high velocities, i.e. the laws of gas dynamics or aerodynamics.

Circuit Interruption

We shall presently review some of the general fundamentals of fluid mechanics and thereafter present a few fundamentals of aerodynamics particularly pertinent to air blast breaker design.

Steady flow of air

Consideration of a steady gas flow is the first step. In a steady gas flow all gas particles successively passing a point fixed in space have the same flow velocity. The path of any gas particle in a steady flow is called a streamline. Obviously, no gas particle can ever flow from one streamline to another. The tangent at any point of a streamline gives the direction of flow. Streamlines drawn through a closed curve generate a stream tube. When considering velocity distribution along a passage of varying cross-sectional area we shall assume that all gas particles flowing across any given cross-section of a stream tube normal to the direction of the flow have the same velocity; this assumption must be dropped when considering the actual velocity distribution across a passage.

Velocity distribution along passage

Figure 1 shows a portion of a passage of a varying cross-sectional area. If there is a steady flow of gas through the passage, a constant amount of gas will flow through any plane, for instance plane I, per unit of time, and equal amounts of gas will flow through each plane, for instance plane I and plane II, in a given time t. This may be expressed by equations

$$v_1 \cdot a_1 \cdot \rho_1 = \text{constant} \qquad \text{(Eq. 1)}$$

and

$$v_1 \cdot a_1 \cdot \rho_1 \cdot t = v_2 \cdot a_2 \cdot \rho_2 \cdot t \qquad \text{(Eq. 2)}$$

wherein v_1 and v_2 are the flow velocities normal to planes I and II, a_1 and a_2 the cross-sectional areas at planes I and II, and ρ_1 and ρ_2 the density of the gas. Equations 1 and 2 express the continuity principle. Where density changes are but little within the field of flow under consideration, ρ_1 may be considered equal to ρ_2. The above equation then becomes

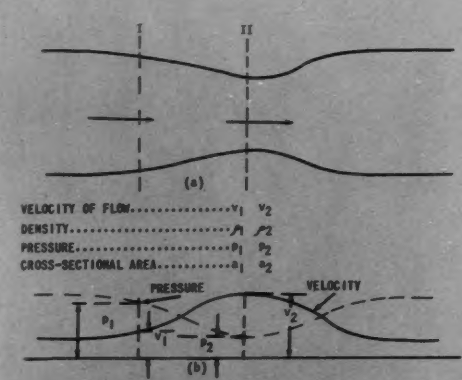
$$v_1 \cdot a_1 = v_2 \cdot a_2 \qquad \text{(Eq. 3)}$$

In words: In a steady flow of gas the flow velocity is greatest where the cross-sectional area is least. This is clearly shown in the diagram of Figure 1.

Pressure distribution along passage

As shown in Figure 1, the flow velocity v_1 is relatively small where the cross-sectional area a_1 is relatively large, while the flow velocity v_2 is relatively large where the cross-sectional area a_2 is relatively small. Hence an accelerating force must be in existence by the action of which the velocity is increased from v_1 to v_2. That accelerating force is, of course, the difference in pressure between the points of large and small cross-sectional area. It follows therefrom that in a steady flow of fluid pressure is greatest where velocity is least.

In a gas flow in which there are no losses the potential or pressure energy prevailing at points of large cross-sectional area may be converted completely into kinetic energy at points of small cross-sectional area and vice versa.



VELOCITY DISTRIBUTION and pressure distribution along a passage is shown in the above drawing. Velocity is small where pressure is high and large where pressure is low. **(FIG. 1)**

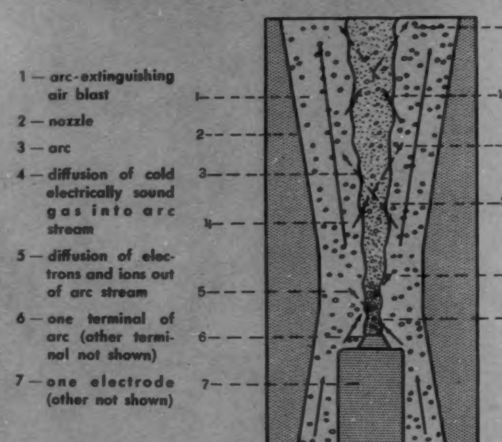
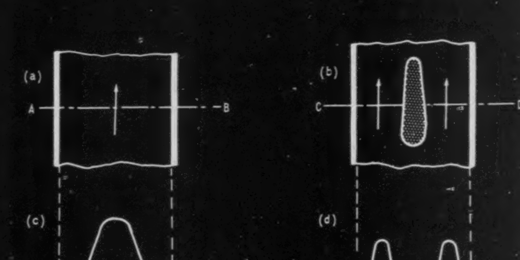


DIAGRAM SKETCH of an arc burning in a nozzle and entirely enveloped by an arc-extinguishing air blast. Electrically sound air replaces ionized air in the arc path. **(FIGURE 2)**



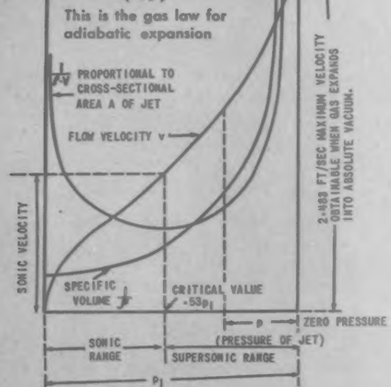
LINE DIAGRAMS showing transverse velocity distribution in a flow of gas. Velocity is at zero at the boundary surface between the gas and the passage walls, and maximum in the middle of the stream. **(FIGURE 3)**

$$v=\sqrt{2\cdot g\ \frac{\gamma}{\gamma-1}\ \frac{p_1}{\rho_1}\left[1-\left(\frac{p}{p_1}\right)^{\frac{\gamma-1}{\gamma}}\right]}$$

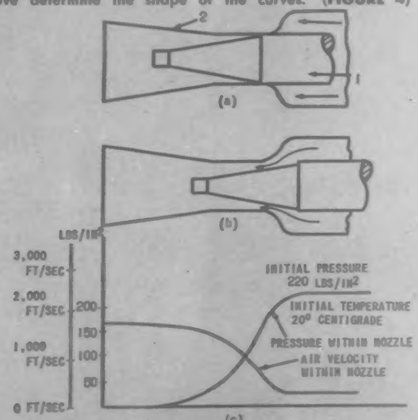
γ is constant. This is the well-known equation for flow velocity; $v\cdot a\cdot\rho=$ constant, which expresses the continuity principle;

$$\rho=\rho_1\left(\frac{p}{p_1}\right)^{\frac{1}{\gamma}}$$

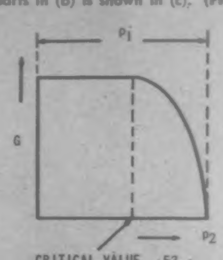
This is the gas law for adiabatic expansion



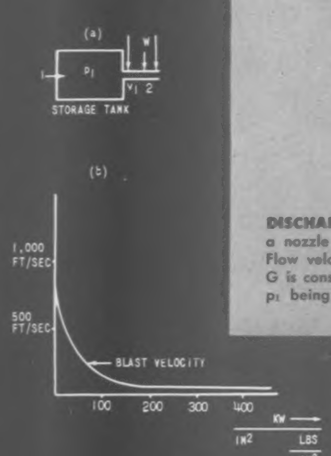
PLOTTED CHARACTERISTICS of a steady flow of a compressible fluid permit the approximate calculation of any desired nozzle and the analysis of any given nozzle. Equations shown above determine the shape of the curves. **(FIGURE 4)**



LINE DRAWING shows air blast breaker for supersonic blast velocities in closed contact position (a) and in the process of contact separation (b). Pressure and velocity distribution along structure for position of parts in (b) is shown in (c). **(FIGURE 5)**



DISCHARGE RATE of compressed air through a nozzle is plotted against back pressure, p_2. Flow velocity v is sonic and rate of discharge G is constant, as long as p_2 is less than $.53p_1$, p_1 being the tank pressure. **(FIGURE 6)**



BLAST VELOCITY at passage entrance is reduced by uniform heat supplied along a passage to compressed air. Diagram plots velocity v_1 in feet/seconds against amount of heat in kw per unit of cross-sectional area in inches^2 of escape passage and per unit of tank pressure p_1 in pounds/inches^2. **(FIGURE 7)**

Effect of flow velocity on flow resistance

The laws of friction are very different for low and high flow velocities. Where the flow velocity is low, flow resistance is proportional to the first power of the velocity; however, where the velocity is high, flow resistance is approximately proportional to the square of the velocity. The change from the first power law to the second occurs suddenly at a critical velocity which depends upon the nature of the gas, the geometrical configuration of the gas conduit and the material of which the conduit is made.

Turbulent gas flow in air blast breakers

The change from the first power law to the second power law occurs in any given gas for any given structure always at the same critical velocity. If that velocity is exceeded, eddies are formed in which the motion of the gas is circular. Circular motion is one of the characteristics of turbulent gas flow. Turbulence occurring in the arcing chamber of air blast breakers tends to increase the rate of deionization. Evidently this is a favorable aspect of turbulence. An unfavorable aspect of turbulence in air blast breakers consists in that it tends to reduce the flow velocity wherever it occurs in the path of the blast. In order to minimize this adverse effect of turbulence, any blast-swept structural element should be streamlined in character.

Momentum transfer in gas flow

Where contiguous layers of a gas have a relative velocity, molecules crossing the boundary from the faster-moving to the slower-moving layer impart momentum to the molecules in the latter. Thus, the original speed of molecules in the slower-moving layer is increased. Molecules crossing the boundary from the slower-moving to the faster-moving layer are accelerated by the molecules in the latter. The momentum transfer involved in that acceleration results in a decrease of the original speed of molecules in the faster-moving layer.

Electrons and ions diffuse within a gas in the same way as gas molecules do. Electrons and ions diffusing out of the arc into the arc-extinguishing blast are progressively accelerated by the blast and finally swept away. Therefore, momentum transfer is the mechanism that makes the air blast breaker tick. Figure 2 illustrates in diagrammatic fashion how electrically charged particles are removed by the blast from the arc path and shows also how electrically sound air diffuses into the arc path replacing the electrically charged particles.

Velocity distribution across passage

Since a rapid flow of gas is decelerated close to the boundary between the flow and a gas layer of lesser flow velocity, one may expect that the flow velocity is zero at the boundary between a rapid gas flow and a fixed wall. This is actually the case.

Gases flowing through passages have zero velocity at the boundary surface between the gas and the walls of the passage. Maximum gas velocity is reached along an axis situated midway between opposite boundary surfaces of the gas flow. There is progressive increase of velocity transversely to the direction of flow from the points of zero flow velocity to the point of maximum flow velocity. These facts which are of great importance with regard to design and operation of air blast breakers were previously disregarded when it was assumed that all gas particles flowing across any given cross-section of a

stream tube normal to the direction of flow have the same velocity.

Figures 3a and 3b show two gas passages of which one is provided with a streamlined partition arranged in the direction of the flow. Figures 3c and 3d indicate, diagrammatically, the velocity distribution along the lines A-A and C-D of Figures 3a and 3b.

An arc exposed to the action of an air blast assumes the position offering minimum drag by orienting itself in the direction of the blast. Its position then corresponds to that of the partition of Figure 3b and it affects the blast in a way similar to a solid partition or impediment inasmuch as it tends to reduce the blast velocity in the immediately adjacent blast layer.

Taking account of compressibility

Figure 4 refers to a steady flow of compressed air escaping from a storage tank through an orifice without friction. The figure covers, in addition to flow into atmosphere, also the case of flow into a receiver at lower than atmospheric pressure. The expansion that occurs as the compressed air escapes from the storage tank is considered to be adiabatic, i.e. without flow of heat into or out of the air flow. Since the product of velocity v, cross-sectional area a and density ρ is a constant in a stationary fluid flow (Eq. 1), the cross-sectional area a is proportional to $\frac{1}{\rho \cdot v}$. Figure 4 shows the velocity v of the jet, the quantity $\frac{1}{\rho \cdot v}$ which is proportional to the cross-sectional area a of the jet and the specific volume $\frac{1}{\rho}$ (the reciprocal of the density ρ) of the air in motion forming the jet plotted versus the pressure p of the jet in percent of tank pressure p_1.

At the left end of the diagram, jet pressure p is equal to tank pressure p_1. Consequently velocity v is zero, cross-sectional area a is infinite and both specific volume $\frac{1}{\rho}$ and density ρ have finite values.

Jet pressure p decreases toward the right of the diagram. Initially, the changes of specific volume $\frac{1}{\rho}$ and density ρ are but small; but both flow velocity v and cross-sectional area a change rapidly, the former increasing, the latter decreasing.

With further decrease of jet pressure p, the velocity v approaches the maximum possible value $v_{max.} = 2{,}483$ feet per second. This is the critical velocity of flow into absolute vacuum. Toward the right end of the diagram specific volume $\frac{1}{\rho}$ increases and density ρ decreases very rapidly. The cross-sectional area a increases asymptotically toward infinite.

There is a minimum cross-sectional area $a_{min.}$ between the descending and the ascending branch of the curve representing the quantity $\frac{1}{\rho \cdot v}$ or cross-sectional area a. The flow velocity for minimum cross-sectional area $a_{min.}$ is sonic velocity in air at the temperature prevailing at the point where the cross-sectional area is a_{min}. Because of previous adiabatic expansion the temperature of the air when flowing through cross-sectional area $a_{min.}$ is lower than its original temperature. Sonic velocity is reached at a point where the ratio $\frac{p}{p_1}$ is .53, i.e. where jet pressure is .53 times pressure p_1.

Figure 4 indicates that air that is allowed to expand after having reached sonic velocity is further accelerated and reaches supersonic velocities. In such a supersonic blast an increase of cross-sectional area goes with a decrease of pressure and an increase of velocity. This is contrary to the behavior of gases at relatively small velocities to which we are more used where a decrease of cross-sectional area goes with a decrease of pressure and an increase of velocity. Supersonic expansion as shown in Figure 4 can be achieved only by means of a nozzle comprising an upstream portion of decreasing cross-sectional area and a downstream portion of increasing cross-sectional area in which expansion takes place in a predetermined way. Such nozzles are known as de Laval nozzles. Where compressed air stored in a tank is discharged through a passage other than a de Laval nozzle, the flow velocity in the passage may reach, but will never exceed, sonic velocity.

Figures 5a to 5c refer to an air blast breaker nozzle designed to achieve supersonic blast velocities. Figure 5a shows the movable male contact, or plug contact, 1, and the fixed female contact, or nozzle contact, 2, in closed position. Figure 5b shows the same contacts in the process of separation, and Figure 5c indicates pressure and velocity distribution along the structure for the position of parts shown in Figure 5b.

Escape of a blast at sonic velocity

Figure 6 refers to a nozzle other than a de Laval nozzle and shows the rate of discharge G plotted versus the back pressure p_2 at the downstream end or exhaust of the nozzle. Tank pressure is designated in Figure 6 by p_1.

The theoretical maximum velocity of a jet of air at the minimum section is that of sound under the conditions existing at that section. No further reduction of the back pressure p_2 can affect distribution of pressure and velocity on the upstream side of the minimum section. Hence the rate of discharge G remains constant over a wide range of back pressures p_2, i.e. as long as back pressure p_2 is less than $.53p_1$.

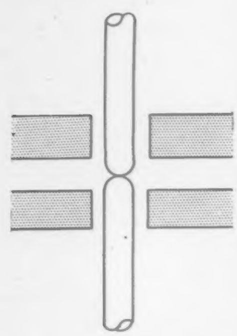
Where back pressure p_2 is atmospheric pressure, tank pressure, in order to be $\frac{1}{.53}p_2$, must exceed 27.93 lbs/in^2. If the back pressure p_2 exceeds the critical value $.53p_1$, both the rate of discharge G and the flow velocity v decrease, the former along a curve which is close to a quarter of an ellipse. Both the rate of discharge G and the flow velocity v become zero when back pressure p_2 increases to such an extent that it becomes equal to tank pressure p_1.

A definite time is needed after blast initiation for accelerating the quiescent mass of ambient air blocking the exhaust of a nozzle or passage to sonic velocity, and steady state conditions are reached only after that time has elapsed.

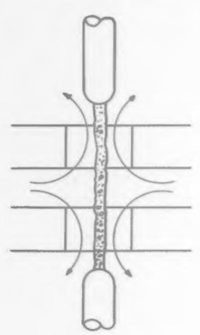
Effect of arc on arc-extinguishing blast

In the nozzle of air blast breakers the pressure on the tank side is always so much higher than atmospheric back pressure that we should expect the steady state blast velocity to reach sonic velocity. Sonic velocity may actually be reached so long as generation of pressure due to the heat of the arc does not increase the back pressure p_2 beyond the critical value of $.53p_1$.

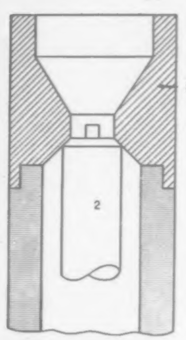
The elliptical portion of the curve in Figure 6 corresponds to flow velocities less than sonic velocity and indicates how the rate of discharge G decreases if the heat generated by the arc is so large that the back pressure exceeds the critical pressure of $.53p_1$.



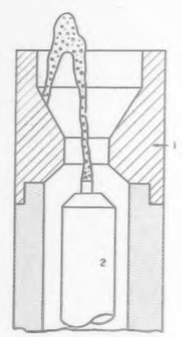
Axial air blast breaker in closed position. (FIG. 8a)



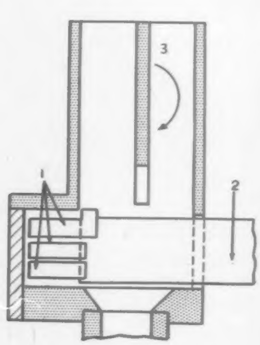
Axial air blast breaker in open position. (FIG. 8b)



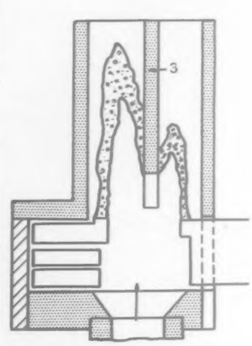
Ruppel type air blast breaker in closed position. (FIGURE 8c)



Ruppel type air blast breaker in open position. (FIGURE 8d)



Cross air blast breaker in closed position. (FIG. 8e)



Cross air blast breaker in open position. (FIG. 8f)

SERIES OF DRAWINGS shows the structural and operating differences of two representative axial air blast breakers and one cross blast breaker in both closed and open positions. **(FIGURE 8)**

If the rate of current flow is increased, while all other conditions remain unchanged, both arc energy and back pressure will increase. At a critical current the arc-extinguishing blast may be completely stopped. If the intensity of the current under interruption is still further increased, the direction of the gas flow in the breaker may be reversed, i.e. there may be a flow of arc products from the arcing chamber toward the breaker tank instead of an air flow from the breaker tank to the arcing chamber. Such a reversal of the direction of flow does not mean that the breaker has reached the very limit of its interrupting capacity and is unable to clear the circuit. As back pressure in the arcing chamber recedes about the time of a natural zero of the current wave, the tank pressure may be able to overcome the back pressure and to establish an effective air blast in the right direction. Thus an arc may be permanently extinguished at the end of a half cycle during which there was a reverse flow of arc products from the arcing chamber toward the breaker tank. Obviously both flow stalling and reverse flow are undesirable results of back pressure. Reverse flow tends to cause rapid deterioration of parts located at the upstream end of the arcing chamber and not adapted to be exposed to the direct heat of the arc.

If the current under interruption is high, the arc-extinguishing blast may be pulsating, and such blast pulsations are often readily audible.

Quantitative aspects of back pressure

While it is not difficult to determine theoretically the rate of discharge and the velocity of an air blast escaping from a compressed air storage tank through an orifice or short passage, the air blast breaker problem is much more complex since the chamber in which the arc is established and extinguished is a passage of considerable length involving friction and turbulence. The study of the air flow through the arcing chamber of an air blast breaker is rendered still more complex by reason of the fact that the arc constitutes a secondary source of pressure, in addition to the primary source constituted by compressed air stored in the breaker tank. The air flow through the arcing chamber of the breaker is the result of the interaction of the pressures of both sources of pressure.

The pressure in the arcing chamber due to the heat generated by the arc tends to establish a gas flow out of the arcing chamber to atmosphere and an opposite gas flow out of the arcing chamber into the breaker tank. Supposing the space defined by the arcing chamber to be subdivided into parallel layers; each such layer will tend to expand due to the heat generated by the arc. This tendency to expand will be least obstructed at the layer situated at the exhaust end of the arcing chamber, where back pressure is substantially equal to atmospheric pressure. The obstruction counteracting the tendency of the hot arc products to expand is greatest at the layer situated at the end of the arcing chamber adjacent the breaker tank where the tendency to expand is opposed by whatever fraction of the full tank pressure prevails at that point. It follows therefrom that during the arcing time the velocity of the blast will decrease from the exhaust portion toward the entrance portion of the arcing chamber. At the exhaust portion, the flow velocity will be close to sonic velocity in air having the temperature prevailing at the exhaust portion.

Figure 7a shows a storage tank 1 for air under pressure having an exhaust passage 2. A source of heat W is assumed to supply heat uniformly along passage 2 to the flow of air escaping through it. Figure 7b shows the velocity v_1 at the

entrance portion of passage 2 plotted versus the amount of heat supplied per unit of cross-sectional area of passage 2 and per unit of tank pressure p_1. It is apparent that the velocity decreases rapidly as the supply of heat is increased.

Thermodynamics and air blast theory

Up to this point the heat and pressure generated by the arc are the only effects of the arc on the flow of the arc-extinguishing blast to which we have given consideration. In other words, the fact that an electric arc is constituted of electrically charged particles — electrons and ions — in addition to neutral gas atoms and molecules, has played no part in our analysis of the flow of the arc-extinguishing blast.

Ionization occurring in high temperature gases which are in the state of thermal equilibrium, where free electrons, ions and neutral gas particles all have the energy of agitation that corresponds to the temperature, may be considered without taking account of the mechanism that causes ionization and of the fact that some of the particles involved are electrically charged particles and others not. Therefore, disregarding the difference between electrically charged and neutral particles, electrons, ions and neutral gas particles may be considered gas particles in random heat motion, i.e. as if they were atoms and molecules in a mixture of different un-ionized gases. In such a mixture, the total pressure is equal to the sum of the partial pressures due to the presence of the different gases. Because of the similarity between mixtures of different gases and mixtures of gases, electrons and ions, the concepts of partial electron pressure and partial ion pressure may be applied to ionized gases in analogy to partial gas pressures. In a similar way, the concept of electron temperature may be formed in analogy to that of gas temperature. Therefore, on the basis of such concepts, the behavior of ionized gases may be analyzed in straightforward thermodynamic fashion.

The electrons in the arc of an air blast breaker are subjected to, and accelerated by, an intense electric field which orients the electrons along the lines of force of the field and precludes scattering of electron velocities directed at random. Hence the concept of electron temperature, which is predicated upon random motion of electrons, cannot be applied literally. Further, because in air blast breakers the electric charges are concentrated in the arc core and diluted in the blast envelope, the ionized matter is not homogenous with its constituent particles in state of thermal equilibrium. Hence, it is not possible to apply straightforward thermodynamics to air blast breakers. It is, however, permissible to apply thermodynamic reasoning to air blast breakers because there is sufficient similarity between arcs and high temperature gas mixtures. The basic concepts of the thermodynamic theory of the air blast breaker are of the kind used in turbine design and jet propulsion rather than the conventional electrical concepts of circuit breaker theory.

Axial and cross-blast breakers

The contacts of air blast breakers may be separated either in the general direction of the blast through the arcing chamber or transversely to that direction. The former arrangement is referred to as axial blast and the latter as cross-blast. The direction of contact separation has no immediate bearing upon the interrupting process as will be shown below, but it determines to a considerable extent the geometry of the breaker as a whole and some of its functional characteristics.

A particular version of the cross-air blast breaker that has gained wide acceptance in this country comprises a widely diverging fishtail-shaped arc chute which includes a plurality of arc-restraining partitions positioned edgewise with respect to the arc. Arc extinction is due in such breakers to the combined action of the blast and of the surfaces of the partitions.

Axial type breakers vary

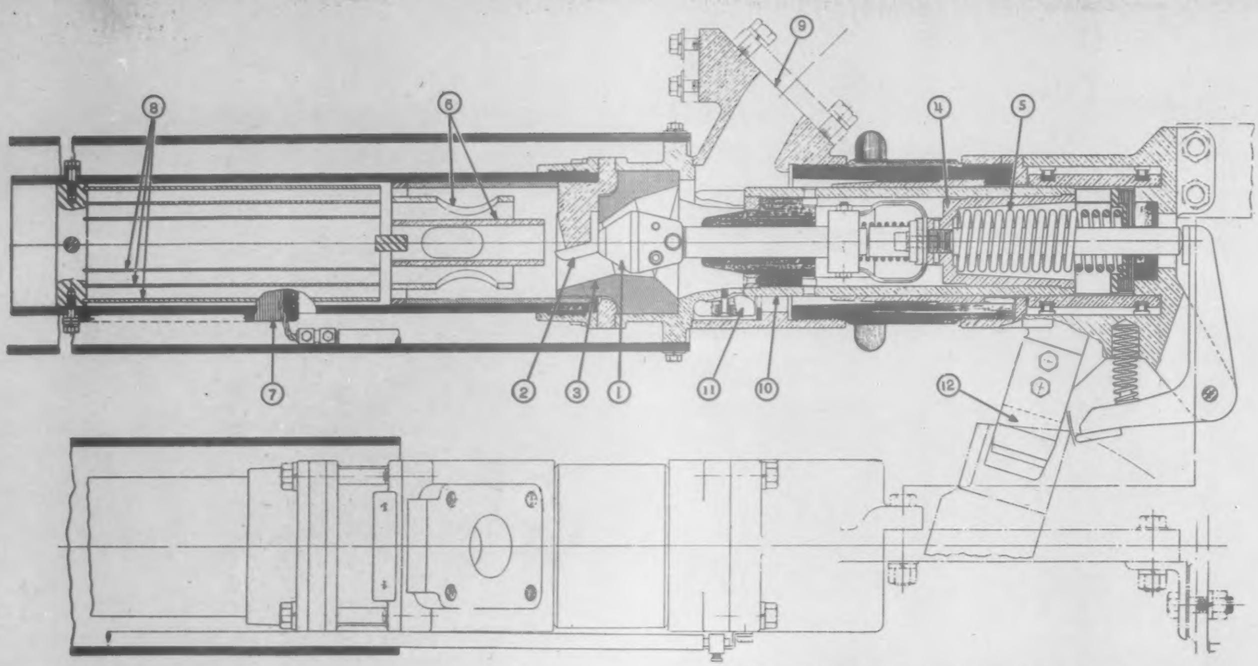
The terms axial blast breaker and Ruppel type breaker have frequently been used as synonyms. Ruppel type breakers are breakers of European origin named after their inventor who pioneered the modern air blast breaker. Ruppel type breakers are of the axial blast type but not all axial blast type breakers are Ruppel type breakers. Figures 8a and 8b show, diagrammatically, an axial blast type breaker which is not a Ruppel type breaker in closed and open position, respectively. The arc-extinguishing blast approaches the arc gap radially through a circular opening and escapes from the arc gap axially in opposite directions, thus providing a cylindrical blast envelope that surrounds the entire surface of the arc.

Figures 8c and 8d show a Ruppel type breaker in closed and open position, respectively. The breaker comprises a stationary nozzle-shaped contact 1 and a cooperating movable plug contact 2 which closes the entrance of the nozzle contact 1 as long as both contacts 1 and 2 are in engagement. The terminal of the arc formed on contact 2 upon separation of contacts 1 and 2 is swept by the blast to the arcing tip on contact 2, from where there is no further escape. The other terminal of the arc, i.e. the terminal formed on nozzle contact 1, is swept by the blast through the nozzle passage and thereafter moved along the flaring downstream portion of nozzle contact 1. The portion of the arc situated immediately adjacent the movable plug contact 2 is surrounded by a cylindrical blast envelope, while the downstream end of the arc loop tends to float away with the blast. Hence, there is little relative motion at the downstream end of the arc loop between the blast and the arc. The conversion of the arc path into an insulator is most rapidly effected at such a point of the arc path where the relative velocity between the arc and the arc-extinguishing blast is highest. That highest relative velocity occurs where the arc extends axially downstream from the movable plug contact and is surrounded by the blast envelope.

Cross-blast breakers

Figures 8e and 8f show a cross-blast breaker in closed and open position, respectively. In the closed position, the stationary finger contacts 1 are engaged by the movable blade contact 2. The arc formed upon separation of contacts 1 and 2 is caused by the blast to loop in downstream direction. A point of the arc is engaged by an arc-restraining insulating barrier 3 arranged edgewise with respect to the arc. Thus the arc is compelled to form a double loop. One half of that loop is situated to the left, and the other to the right of the arc-restraining edge of barrier 3. The double arc loop comprises four sections assuming the position that offers minimum drag and extending substantially in the direction of the blast. The downstream ends of the double loop tend to float away with the blast, as in the case of the Ruppel type breaker. At the sections of the arc extending in the direction of the blast there is a high relative velocity between the arc and the blast. It is along these sections where ionized gas is most rapidly replaced by electrically sound gas.

Whatever cross-blast effect there may be at the point or points of the arc situated farthest downstream, either in Ruppel



1 — conical butt movable arcing contact
2 — angular butt stationary arcing contact
3 — insulating nozzle member
4 — contact-opening piston
5 — contact-closing spring
6 — probe electrode
7 — resistor
8 — cooling structure
9 — admission of air blast
10 — movable main contact
11 — stationary main finger contacts
12 — stationary contact of isolating disconnects

IN HYBRID BREAKER shown, air blast admitted at 9 acts on piston 4, parting current carrying contacts 10 and 11 and then arcing contacts 1 and 2. Movable arcing contact 1 releases air blast to flow between contacts 1 and 2 to interrupt arc. Contacts reclose in reverse order under action of contact closing spring 5 after disconnect switch opens. Closing disconnect switch at high speed is all that is necessary to close the circuit. Although shown horizontally, unit is operated in vertical position. **(FIGURE 9)**

type breakers or in cross-blast breakers, such effect is of little moment with regard to arc extinction since at this point, or these points, there is little relative velocity between the arc and blast.

In both the axial blast and the cross-blast breaker the direction of the arc and that of the blast are substantially at right angles at the time of arc initiation. The blast-exposed arc adjusts itself to the blast action by assuming the direction of the blast. At the time of arc extinction substantially the entire arc path extends in a direction longitudinally of the blast.

Hybrid breakers combine good points

The fact that the axial blast type as well as the cross-blast type breaker have certain particularly desirable features is conducive to designing breakers that combine the advantages of both types and eliminate the disadvantages of either type. In Ruppel type breakers, owing to the operation of the contacts in the fashion of a valve, following opening of the blast valve pressure is being built up immediately adjacent to the contacts up to the very instant of contact separation. This is a desirable feature of Ruppel type breakers. The type of contact used in the Ruppel type breakers does not lend itself very well to carrying of high currents. Where very high current carrying capacity is required, better performance can be expected from contacts particularly suited for that requirement.

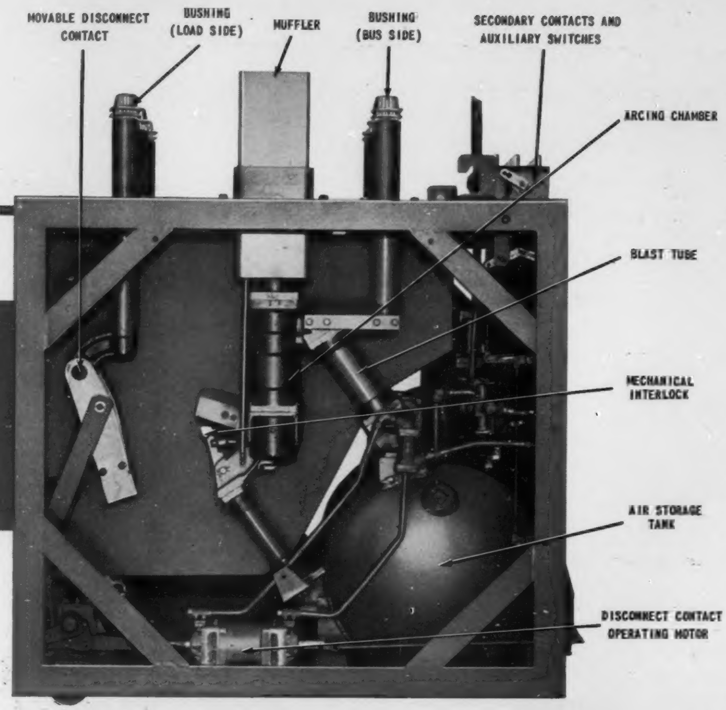
Figure 9 shows the arcing chamber and the parts immediately associated with it of a hybrid design referred to as skew blast combining desirable features of axial and cross-blast type breakers. The arc is drawn between a movable conical butt contact and a fixed angular butt contact forming an arc horn and arranged on the downstream side of the conical butt contact. Both contacts are surrounded by a nozzle member of insulating material. The conical contact and the nozzle member cooperate to control the arc-extinguishing blast. The blast escaping upon separation of both contacts forms an envelope completely surrounding the conical contact. Owing to the geometry of the insulating nozzle member there is a preponderance of the blast across the gap formed between the separated contacts transversely to the direction of contact separation. That intense transverse component combined with a transverse magnetic bias of the arc causes the arc to loop laterally.

Surface action of the insulating nozzle member plays a part in the interrupting process if and when the combined air blast bias and magnetic bias of the arc impels the latter into engagement with the nozzle member. After extinction of the arc formed between the two butt arcing contacts a disconnect switch opens the circuit at another point, whereupon the butt arcing contacts are caused to reengage by the action of a helical operating spring. That spring is arranged in an operating piston for opening the butt arcing contacts.

Figure 10 shows the general arrangements of parts in a breaker of the type shown in Figure 9 including the arrangement of the disconnect switch in series with the butt arcing contacts. Figure 11 shows the application of a breaker of the type shown in Figure 10 to vertical lift metal-clad switchgear.

Interruption of high currents

Extinguishing a high current arc in an air blast breaker means



ARRANGEMENT OF PARTS in hybrid breaker. Muffler and arcing chamber are situated between axes of bushings which form terminal elements. The current path through breaker is substantially U- or loop-shaped, and all structure at ground potential is external to current loop. **(FIGURE 10)**

to cope successfully with the back pressure generated by the heat of the arc.

The diameter of high current arcs is large and may be large enough to fill the entire cross-sectional area of the arcing chamber or blast passage. Whenever this occurs, the blast may be completely stopped. If the cross-sectional area of the blast path is larger than that of the arc, the blast will more readily be able to by-pass the arc and less liable to be stalled.

Extinction of high current arcs requires high tank pressures to overcome the high back pressures resulting from high currents. The tank pressure in commercial air blast breakers is generally in the order of 120 to 250 lbs/in^2. Extinction of high current arcs requires also arcing chambers of large cross-sectional area and involves consequently consumption of relatively large amounts of compressed air.

Figure 12 illustrates the effect of the relative sizes of the nozzle and arcing chamber in the case of the Ruppel type and the cross-blast type breaker.

High current arcs have the tendency to increase the temperature of the contacts resulting in thermionic emission and contamination of the arc gap by metal vapors. Thermionic emission and evolution of metal vapors may persist several hundredths of a second after the arc has been extinguished.

Low current interruption

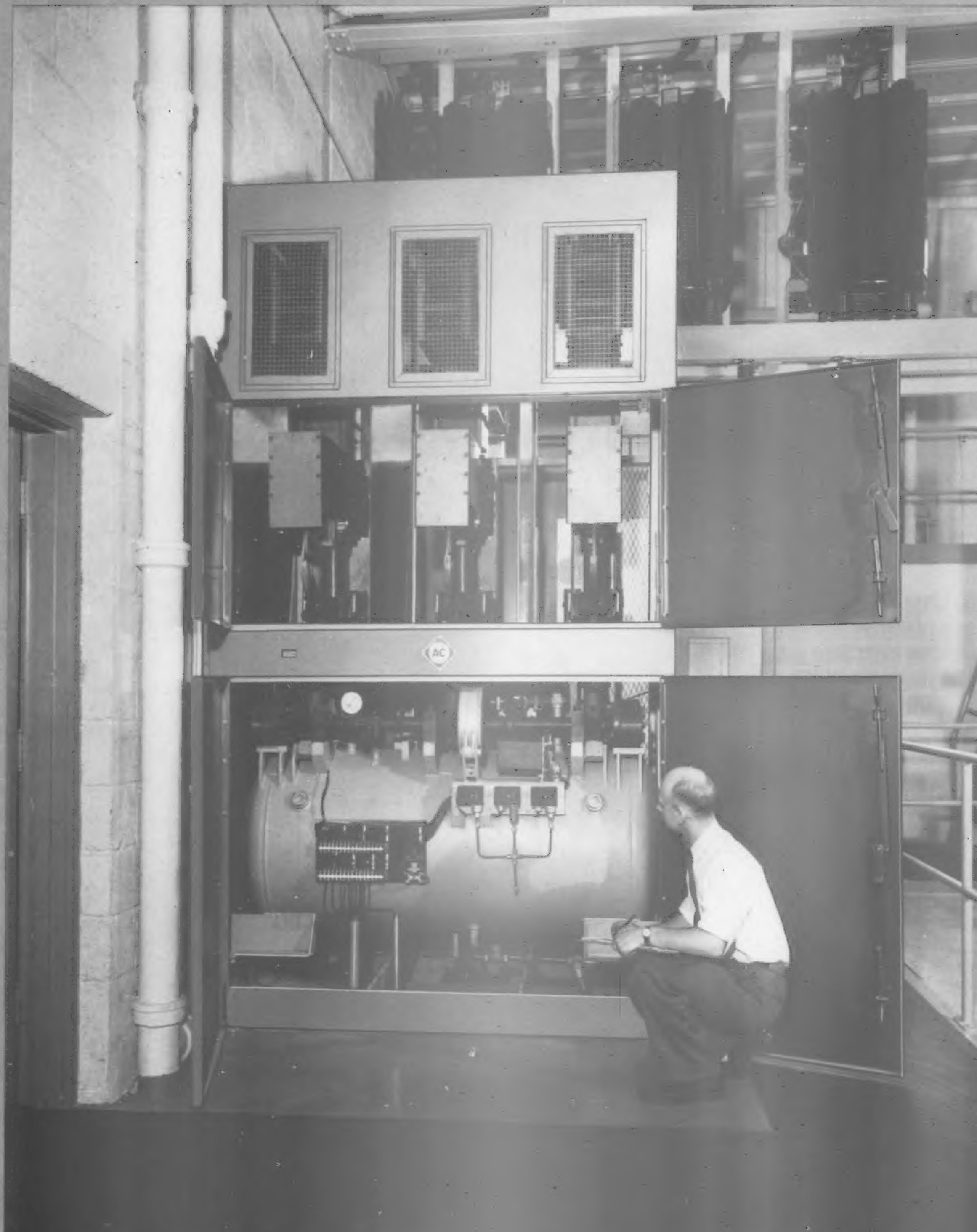
Small current arcs tend to be more rapidly deionized than high current arcs because they involve smaller amounts of ionized gas and because deionization is not limited substantially to the surface layer of the arc core as in the case of high current arcs, but takes place substantially throughout the entire core space. Another reason accounting for more rapid deionization of small current than of high current arcs is the higher tendency of the former to loop and be elongated in turbulent gas flows.

If arcs of a relatively small magnitude are subjected to an intense arc-extinguishing blast, the rate of deionization of the arc path may be so rapid that the current is reduced to zero substantially prior to the time of a natural zero of the current wave. This phenomenon is referred to as chopping of the current wave. In that particular case, ac circuit interruption is achieved in d-c circuit interrupting fashion by increasing the arc voltage and without relying on the deionizing effect inherent in natural current zeros.

In general, air blast breakers are primarily designed for interrupting very high currents, and if an air blast having sufficient intensity to extinguish a very high current arc is allowed to act upon an arc of much lesser magnitude, much more rapid deionization of the arc path may be expected. If there is a substantial amount of inductance in the circuit, the rapid rate of change of current combined with the effect of the circuit inductance may give rise to an inductive voltage kick or voltage surge. The magnitude of that inductive voltage is determined by the fundamental voltage current equation for the purely inductive circuit

$$e = -L \frac{di}{dt} \qquad \text{(Eq. 4)}$$

wherein L is the circuit inductance and $\frac{di}{dt}$ the rate of change of current. A typical, if not the most important, case where both the inductance L and the rate of change of current $\frac{di}{dt}$



THIS CROSS AIR BLAST circuit breaker, having a rated interrupting capacity of 1,500,000 kva (2,000 amps) at 15 kv, has compressed air storage tank at bottom and exhausts for the arc products of the three poles behind grilles at top of the metal housing. The three arc chutes are clearly visible below the grilles, while the blast tubes can be seen below the arc chutes. Blast paths from tank to arc chutes are approximately straight lines.

are high is the interruption of magnetizing currents of unloaded transformers. Limitation of inductive voltages to safe values is an important consideration in the design of air blast breakers.

Application of air blast breakers for interrupting charging currents of long transmission lines and cables and the switching of large capacitor banks involves interruption of the relatively small currents which flow in a predominantly capacitive circuit. We have seen when considering the relation between circuit and circuit breaker that in capacitive circuits the rate of rise of the recovery voltage is relatively small, but that the value to which the recovery voltage may rise lies considerably above the normal line voltage. Therefore capacitive circuits require interrupting devices capable of deionizing the arc path at a rapid rate, precluding restriking after current zero by the rising recovery voltage. The air blast breaker is inherently suited for interrupting capacitive circuits since the high flow velocity of its arc-extinguishing medium endows the breaker with the ability of rapidly deionizing the arc path.

Shunting of an arc by a resistor

Where an arc is shunted by a resistor, a part of the arc current is diverted to and flows through the resistor, resulting in a decrease of the arc current. Owing to this initial decrease of the arc current, the rate of deionization of the arc path and the resistance of the arc will increase, causing a further increase of the portion of the total current that flows through the resistor. This process of decrease of arc current and increase of resistor current is continuous. Its final result may be complete substitution of the current path through the resistor for the current path through the arc, i.e. complete extinction of the arc. The same occurs where a section of an arc rather than an entire arc is shunted by a resistor. Figure 13 illustrates sequential phases in the process of extinction of a section of an arc that has been shunted by a resistor.

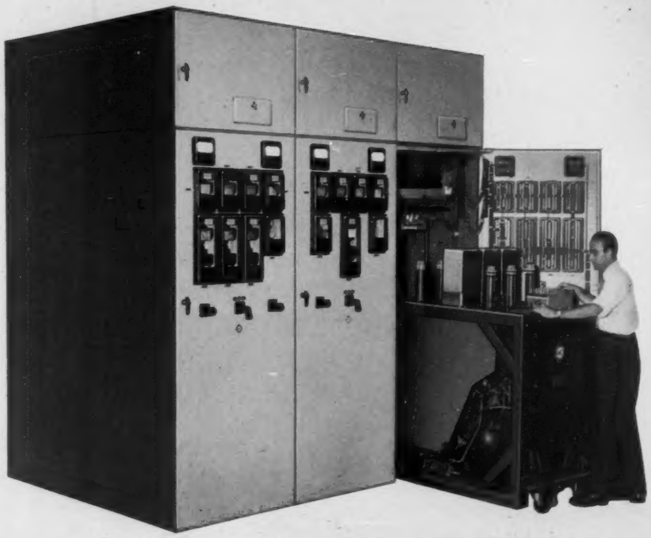
Where the resistor-shunted arc, or arc section, is subjected to an intense deionizing action, as may be the case in an air blast breaker, extinction of the arc and substitution of the arc path by the metallic current path through the resistor requires considerably less time than half a cycle of the current wave.

Resistor shunting of an arc is a most effective method of arc suppression and insertion of resistance into a circuit.

Upon substitution of the current path through the arc by the current path through the resistor, the current flowing through and limited by the resistor must be interrupted. This is achieved at an additional arc gap arranged in series with the resistor.

Where a low current arc in a highly inductive circuit is shunted and subsequently substituted by a resistor of relatively high ohmic value, the counter emf set up in the resistor due to current flow limits the inductive surge voltage to safe values, say 1.5 times the peak value of the circuit voltage. In such an arrangement the magnetic energy stored in the circuit inductance L is converted in the resistor into heat, and then dissipated.

Where a high current arc is shunted and subsequently substituted by a resistor of relatively low ohmic value, the resistor will limit the rate of rise of the recovery voltage across the additional arc gap provided for interrupting the resistor current, and thus the interrupting capacity of the breaker may be considerably increased. Control of the rate of rise of the recovery voltage by arc-shunting resistors is particularly important where, due to the flow of high currents, the amount



SKEW BLAST circuit breaker, combining the advantages of axial blast and cross blast breakers, is rated up to 500,000 kva at 15 kv. This hybrid breaker shown in withdrawn position was designed for installation in a metal-clad, vertical-lift switchgear shown above. (FIGURE 11)

of residual ionization in the arc gap at current zero is relatively large, resulting in a relatively low arc reignition voltage.

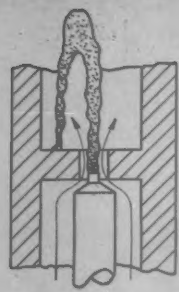
Figure 14 is a cathode ray oscillogram of the voltage across the contacts of an air blast breaker during an extremely severe interruption of a high current without use of a resistor for limiting the rate of rise of the recovery voltage. The peak of the recovery voltage would have been smaller and its damping more rapid had such a resistor been applied.

As indicated, control of the inductive surge voltage generated when interrupting small currents in highly inductive circuits by a high intensity air blast calls for shunt resistors of high ohmic value, while control of the recovery voltage when interrupting high currents call for shunt resistors of relatively low ohmic value. Although these two requirements are evidently contradictory, commercial breakers having one judicially selected resistor can handle almost any situation. Sequential insertion into the circuit of a resistor of low ohmic value and of a resistor of high ohmic value is a measure that may be indicated in extreme cases.

Air blast breakers gain popularity

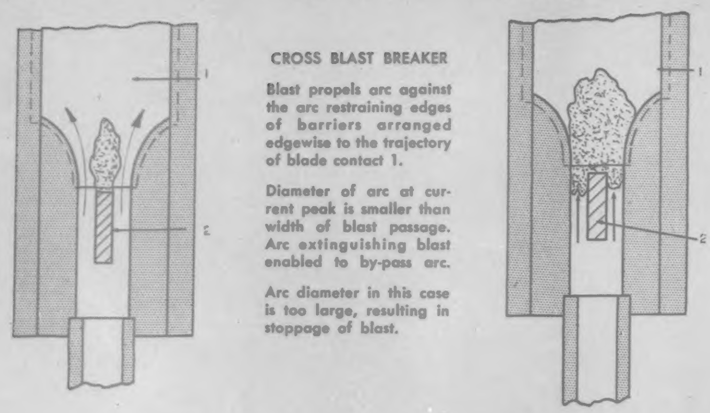
The air blast breaker made its appearance on the American scene about ten years ago. Its scope of application has increased rapidly and continually since then. This type of breaker has become a worthy competitor of oil and air magnetic breakers for indoor service in the medium interrupting capacity, medium high-voltage field covering the range of interrupting capacity ratings from 250,000 to 500,000 kva up to voltage ratings of 15,000 volts. All three types of breakers frequently form an integral part of metal-clad switchgear.

The air blast breaker is rapidly gaining in favor in the high interrupting capacity, medium high-voltage field covering a range of interrupting capacity ratings from one to two and a half million kva, mostly at the standard voltage of 13.8 kv used indoors in power stations.



AXIAL BLAST BREAKER (RUPPEL TYPE)

At current peak, the diameter of arc is smaller than the nozzle diameter. Arc extinguishing blast is enabled to by-pass arc.

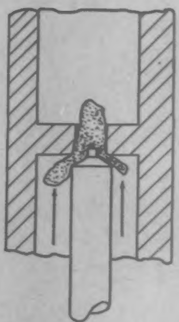


CROSS BLAST BREAKER

Blast propels arc against the arc restraining edges of barriers arranged edgewise to the trajectory of blade contact 1.

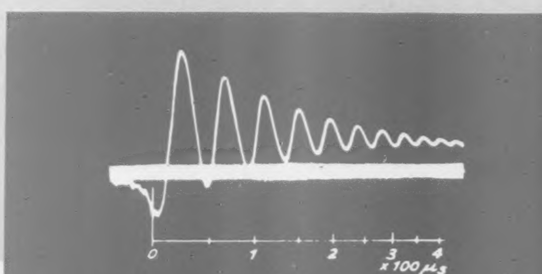
Diameter of arc at current peak is smaller than width of blast passage. Arc extinguishing blast enabled to by-pass arc.

Arc diameter in this case is too large, resulting in stoppage of blast.



At current peak, arc diameter is too large to permit passage of the arc through nozzle, resulting in stoppage of blast.

DIAGRAMMATIC DRAWINGS showing the effects of nozzle and arcing chamber sizes on high current arc extinction in Ruppel and cross blast type breakers. (FIGURE 12)

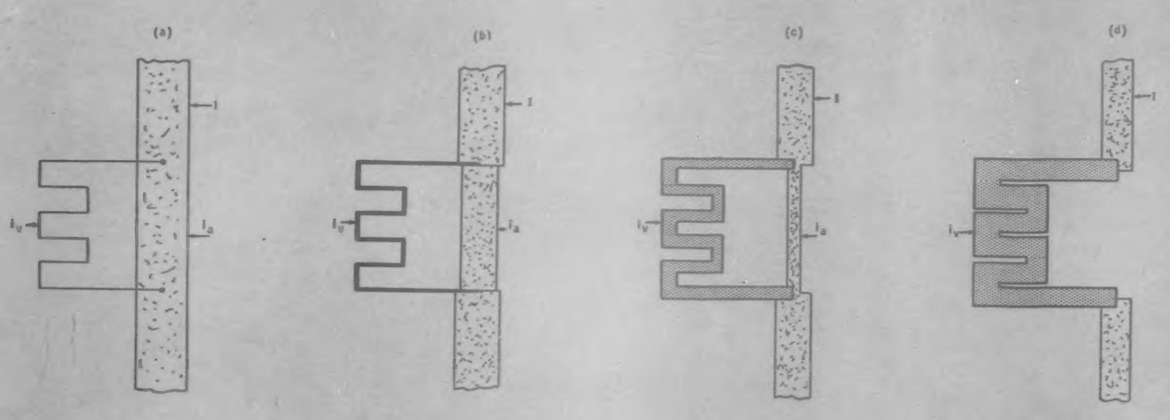


CATHODE RAY oscillogram of the recovery voltage appearing across the contacts of an air blast breaker after a high current shot. The natural frequency of the circuit is high and so is the rate of rise of the recovery voltage and its peak value. Such conditions can be greatly improved by inserting a resistor into the circuit during the circuit interrupting process. (FIGURE 14)

To date, air blast breakers have not gained acceptance in this country in the high-voltage outdoor breaker field ranging from 46 kv upward. A fair number of experimental breakers, however, have been installed.

The features offered by the air blast breaker include high speed operation, elimination of oil, pre-storage of the interrupting medium in ready-to-act form, convenient provision of means for recovery voltage control, suitability for repetitive duty and high speed reclosing, mechanical simplicity and cleanliness of maintenance and operation. Some of these features make air blast breakers particularly suitable for certain applications.

It is perhaps a little early to predict the position that the air blast breaker will ultimately take relative to that of other types of power circuit breakers. Its popularity is increasing. Developments indicate that air blast breakers may be made available in a wider range of voltages and interrupting capacities, particularly for indoor station type application, and probably for outdoor supervoltage applications where extremely high operating and reclosing speeds are needed.



Arc current $i_a = I$
Resistor current $i_v = 0$

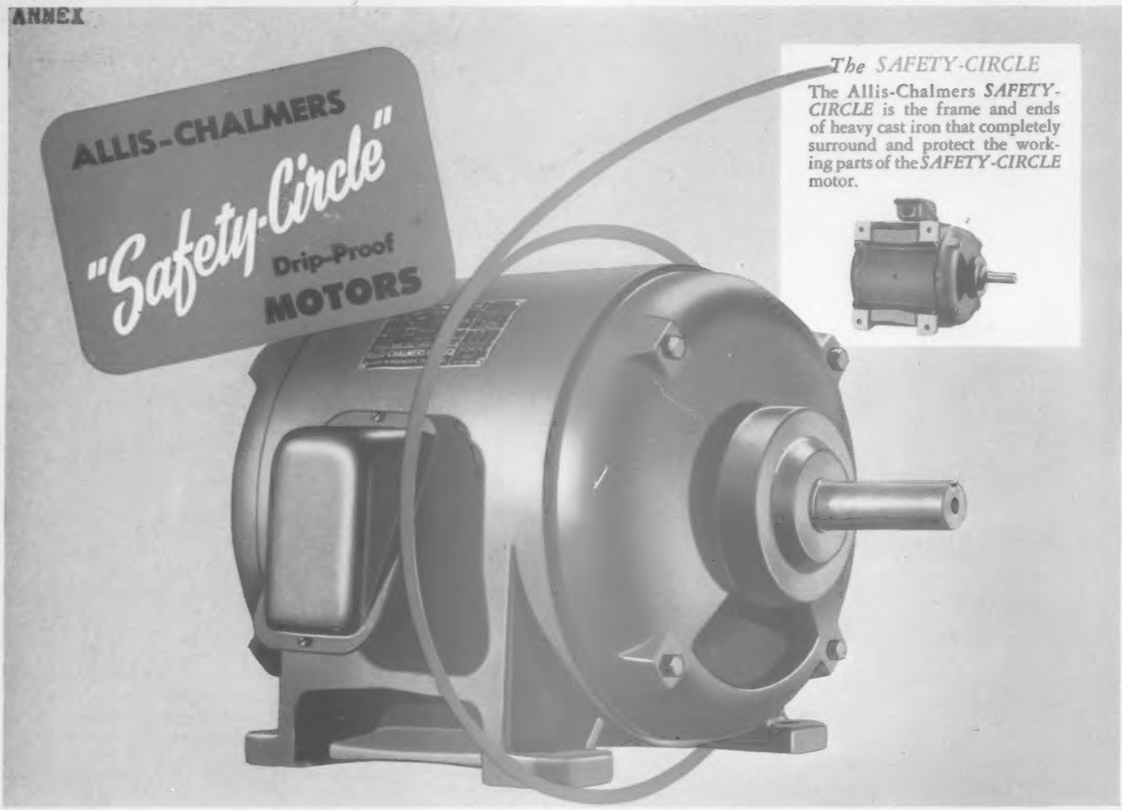
Arc current reduced
Resistor current increased

Arc current further reduced
Resistor current further increased

Arc current between terminals of resistor zero
Resistor carries the entire current.

SKETCHES SHOW that where an arc exposed to the action of an air blast is shunted by a resistor, it becomes unstable rapidly and will soon be extinguished, whereupon the resistor will carry the entire current. The current carried and limited by the resistor is much smaller than the original current. (FIGURE 13)

B. A. STORAASLI
TRANSFORMER
M. O. ANNEX



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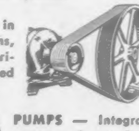

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